FACIES ANALYSIS AND SEDIMENTATION OF THE DELHI GROUP SANDSTONE, BAYANA BASIN, BHARATPUR DISTRICT, RAJASTHAN

ABSTRACT

THESIS

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ABSTRACT

This work presents the results of a detailed description of ten outcrop sections in seven Delhi Supergroup formations in Bayana basin, aiming at an interpretation of depositional processes and sedimentary environments in different localities of the study area to summarize a depositional model as well as to document the sandstones petrography, diagenetic aspects etc. to suggest possible interpretation of the provenance and tectonic setting.

The Delhi basin extends over a strike length of more than 700 km in NE-SW direction and has a maximum width of 120 km in the northeast Rajasthan. In its northeastern part, the Delhi basin consists of several structural depositories, which receive 3-10 km thick volcanic and sedimentary successions belonging to Delhi Supergroup. The Bayana basin defining eastern most limit of the great Delhi basin is a fossil graben with over 3000m thick metavolcanics and metasedimentary successions. The Bayana basin is located 45 km south-west of Bharatpur. It is confined between latitudes $26^0 53'$ and $27^0 02'$ north and longitudes 77^0 $00'$ and $77^0 18'$ east. The infillings Bayana basin is composed of around 3000m thick metasedimentaries and metavolcanics sequence of conglomerates, sandstones, shales, basal volcanic flows and volcanoclastics having faulted contact with pre-Delhi rocks along its southeastern fringe. Stratigraphically, Bayana basin successions can be classified into 3 groups separated by two unconformities. Each of this group has been further sub-divided into formations and members in conformity with the 'code of stratigraphic nomenclature of India'.

A heterogeneous assemblage of conglomerate, sandstones and shale occur as scattered outcrops in the study area. In the present work, seven Lithostratigraphic sections representing seven formations of Delhi Supergroup are examined in ten different localities. Generally the Bayana sandstones exhibit variable colors of pink, brownish yellow, yellow etc. Most of the sandstones are hard and compact, massive although friable occasionally. The lithofacies exhibit vertical variations in the primary sedimentary structures. These structures include planar and trough cross-bedding, herring-bone cross-bedding, ripple marks, channel sandstone body,

laminations etc. Lithostratigraphic sections are measured and are analyzed in the field, representative sandstone samples are collected for petrographic examination. The study is based on 106 samples. The sandstone samples were cut into standard petrographic thin-sections. They were stained with cobaltinitrate for potassium feldspar recognition. 250 to 300 grains were counted per thin section. The traditional methods (Ingersoll et al. 1984) were used to classify and tabulation of grain types. Standard petrological techniques using a polarizing microscope were employed to describe the thin sections. Authigenic components (cement and matrix replacement constituents) were counted separately. The heavy mineral separation was done by following Carver (1971), and identification was undertaken following Krumbein and Pettijohn (1938) as well as Milner (1962). Taylor (1950) method was applied for the study of the nature of detrital grain contacts and for computation of contact index, the method of Pettijohn et al. (1987) was used. The diagenetic process of sandstones was taken into account to check the modification of original detrital composition while attempting interpretation of provenance. Detrital mineralogy of the sandstones, including light and heavy mineral fractions were studied for the purpose of petrographic classification of the sandstones and interpretation of their provenance. Classification schemes of Folk (1980) based on composition of detrital constituents and Dickinson (1985) scheme based on the tectonic setting of the provenance were used.

Fourteen lithofacies are defined based on lithology, sedimentary structures, geometry and palaeocurrent directions. The lithofacies are named and coded individually following Miall's (1977) scheme. The depositional processes and environment have been employed to categorize four main genetic lithofacies assemblages. Facies assemblage A is constituted of lithofacies like tabular/trough cross-bedded sandstones, herring-bone cross-bedded sandstones, interbedded sequence of clast-supported polymictic conglomerate and sandstone, matrix-supported conglomerate interbedded with medium to fine grained, cross-bedded sandstones etc and represents tidally influenced fluvial deposits. Facies assemblage B consists of a tabular package of tabular cross-bedded sandstones, herring-bone cross-bedded sandstone, trough cross-bedded sandstones, ripple-bedded sandstones, parallel laminated sandstones along with interbedded shale-thinly bedded fine grained sandstone facies and it represents Tidalflat/Intertidal deposits. Facies assemblage C represents Tidal channel deposits and is characterized by the presence of four lithofacies; large scale trough cross-bedded sandstones, large scale tabular cross-bedded sandstones, parallel-laminated sandstones and channel sandbodies. Finally, Facies assemblage D represents Wave & storm dominated Shoreface Deposits and is made up of symmetrical & asymmetrical ripple bedded sandstones, interference ripple-bedded sandstones, tabular and trough cross-bedded sandstones in large as well as small scale, swaley-type trough cross-bedded sandstones, hummocky cross-bedded sandstone, laminated sandstones and pebbly sandstones facies. These contrasting palaeoenvironmental settings suggest deposition at a basin margin, through several episodes of transgression and consecutive regression, evidence of which are well-documented in the study area. Bimodal to quadrimodal distribution pattern of palaeocurrent for different formations of Bayana basin indicate dispersal of sediment by multidirectional currents in nearshore shallow marine environment (Klein 1967, Selley 1968). The composite distribution of cross-bedding azimuths aggregated from the study area indicates dispersal of sediments from four different directions, indicating multidirectional clastic transport in offshore, onshore and longshore direction (Singh 1991). The source rocks were most probably the Dausa uplift as well as Rajputana Craton (Singh 1985) as the Bayana sedimentary rocks rest on the Archean basement (BGC) and Proterozoic Supracrustals (Aravalli Supergroup) with a pronounced unconformity in between.

Petrographic studies reveal that average grain-size is 2.04 Φ, grains are moderately well sorted. Most of the grains are subangular to subrounded and have low sphericity. Bivarient plotting of various parameters shows the relationship between mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting as moderate (positive as well as inverse). Overall texture of the Bayana basin sandstone can be considered as submatured. According to Folk (1980) classification, the sandstones are mainly quartzarenite. The framework grains are mainly quartz (>90 % of rock volume) and less frequently of feldspar, rock fragments and heavy minerals. Most of the quartz grains are monocrystalline, rest being polycrystalline. The monocrystalline quartz generally shows undulatory extinction. Polycrystalline quartz grains possess both sharp and sutured intercrystalline boundaries. Feldspars include Plagioclase, oligoclase and microcline, altered to some extent. Both biotites as well as large flakes of muscovite mica are observed. Rock fragments include chert, shale, schist, quartzites etc. Average detrital mineralogy includes monocrystalline quartz (84.68 %), polycrystalline recrystalized quartz (4.18 %), stretched metamorphic quartz (2.36 %), feldspar (3.98 %), mica (1.09 %), rock fragments (3.43 %) and heavy minerals (0.27%). Average compositions of heavy minerals in these samples are as follows: opaque (87.6 %), tourmaline (3.35 %), biotite (3.1 %), muscovite (2.5 %), garnet (1.0 %), epidote (0.5%), zircon (0.5%), rutile (0.5%), and staurolite (0.5%).The detrital grains of Bayana basin are in the sand size range and derived from only 100 km distance from Dausa uplift and Rajputana craton (Singh,1985). Due to presence of small amount of feldspar and rock fragments in the studied sandstone, prolonged reworking and presence of high gradient stream is quite likely within the basin. The studied sandstones are divided into two groups on the basis of diagenetic features like one group that was subjected to more compaction than cementation and other group that was subjected to more cementation than compaction. In Nithar, JGV Bayana, Damdama and Weir sandstones, silica and iron oxide are the dominating types of cement. The Jogipura Sandstones show dominance of carbonate, silica and barite cements. In Badalgarh Sandstones, diagenetic studies showed that silica is the dominating types of cement. ·The sandstones consist of silty and clayey matrix. The matrix compositionally represents fine grained monocrystalline and polycrystalline quartz, mica as muscovite and sedimentary as well as metamorphic rock fragments like siltstones, quartzite, schists, volcanic lithics and feldspars. In Nithar and Jogipura sandstones matrix is clayey (post depositional). Bayana sandstones show silty (syndepositional) matrix. The framework constituents of the Bayana basin sandstones exhibit mainly point contacts (67%) followed by long contacts, which explains the high value of average contact index in the studied samples. Porosity of the sandstones is studied in terms of existing optical porosity (EOP) and minus cement porosity (MCP). Average percentage of EOP is 3.92 and average MCP percentage is 17.83. The primary porosity of the rock is reduced by compaction and cementation through mechanical processes in the early stage of diagenesis, and through chemical processes in the later stage, which finally resulted in generation of secondary porosity. Generation of secondary porosity influenced the minus cement porosity to increase. Compaction, largely influenced by roundness of detrital particles was possible in the absence of an early major cementation phase that could have stabilized the detrital framework. Major diagenetic event was alteration of feldspars, dissolution. The feldspar grains show different stages of alteration. At places, complete dissolution of feldspar grains resulted in oversize pores. Dissolution and loss of feldspar can take place in the shallow weathering zone or in the deep surface (McBride, 1985). The shallow depth of burial and lack of illitization suggest that the feldspar in the studied sandstones were destroyed in the shallow weathering zone. Investigation of heavy mineral types revealed the occurrence of zircon, tourmaline, and rutile which suggest an origin from igneous (plutonic) source rocks. Again, presence of epidote, garnet and staurolite indicate a source in metamorphic rocks (Morton et al. 1992; Wanas et al. 2006). Thus the suite of heavy mineral in the Bayana sandstones indicates source rocks which differ from igneous to metamorphic.

To understand the tectonic settings of the Bayana Basin sandstones, all the petrofacies were plotted in the Qt-F-L, Qm-F-Lt, Qp-Lv-Ls, Qm-P-K standard diagram, given by Dickinson (1985). The characteristic of the source terrains along the suture zones is large compositional range of the rocks (e.g., suture zones of Himalaya, Apennines and Pyrenees), which supply sediments to the adjacent basin. The large scale compositional variation of the Bayana sandstones also reflects the existence of a similar source terrain for these sandstones. However, in the entire suture zone, sandstones in general are more feldspathic than those of the modern and ancient foreland basins (Dickinson, 1985; Decelles and Hertel, 1989). Most of the foreland basin sandstones plot in the recycled orogen field having fairly uniform composition (Dickinson, 1985) reflecting the dominance of sedimentary source rocks that are lefted and eroded from the thrust sheet and deposited in the foreland basin. Therefore, the second possibility appears more appropriate for the Bayana sandstones. The Qt-F-L diagram which emphasizes factors controlled by provenance, relief, weathering and transport mechanism is based on total quartzose, feldspars and lithic content. Most of the samples lie in continental block provenance field suggesting contribution from the craton interior with basement uplift. Rest of the samples fall in the recycled orogen provenance which suggest their derivation from metasedimentary and sedimentary rocks that were originally deposited along former passive continental margins (Dickinson, 985). The Qm-F-Lt plot showed that the samples fall in Continental block provenance with little contribution from the Recycled orogen Provenance. In the Qm-P-K diagram, the data lie in the Continental block provenance reflecting maturity of sediments and stability of source area. In Qp-Lv-Ls plot, the sample data mostly fall in the mixed orogenic sand provenence with contribution from arc orogen source and fold thrust belt source. Here analysis of data from the plotting of triangular diagram doesn't exactly suggest the same interpretation which is due to the weathering and post-diagenetic modification of the unstable minerals. Considering the analysis of data plotted on different triangular diagram, a tectonic collage can be suggested as tectonic setting. This interpretation is also supported by the evolutionary history of the Bayana Basin.

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CERTIFICATE

Chayanika Saikia carried out this research on **"FACIES ANALYSIS AND SEDIMENTATION OF THE DELHI GROUP SANDSTONE,BAYANA BASIN, BHARATPUR DISTRICT, RAJASTHAN."**, under my supervision at the Department of Geology, Aligarh Muslim University, Aligarh.

I certify that the research work is an original contribution of the candidate and she is allowed to submit the thesis for the award of Ph D. degree of the Aligarh Muslim University, Aligarh.

a. m. ahmad 7.10.9
(Dr. A.H. M. Ahmad)
Ph D. (Aligarh)
Reader

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It is a matter of great pleasure for me to submit my Ph.D. Thesis on "Facies Analysis and Sedimentation of the Delhi Group Sandstone, Bayana Basin, Bharatpur District, Rajasthan", submitted for the Degree of ***Doctor of Philosophy*** in Geology, Aligarh Muslim University, Aligarh.

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Saikia

(Chayanika Saikia)

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Introduction

CHAPTER - I

INTRODUCTION

Among the various cratons of Indian shield, three cratons, viz., Dharwar, Singhbhum and Aravalli had evolved about individual Archean nuclei. Lithologically these cratons comprise a series of supracrustal sedimentary and volcanic rocks along with iron-manganese formations.

The Aravalli craton of north-west Indian shield bears signatures of major geological and tectonic events spanning over a large part of Precambrian and preserves complete rock record from Archean to Neoproterozoic. Four major regional tectono-magmatic and metamorphic events occurred in this region with ages ~ 3000 Ma (Banded Gneissic Complex), ~ 1800 Ma (Aravalli orogeny), ~ 1100 Ma (Delhi orogeny) and 850-750 Ma (Post-Delhi magmatic events) (Deb et al.' 1989, 2002).

Aravalli Mountain Range (AMR) forms main edifice of Aravalli craton. It separates rocks of Marwar Supergroup (Trans-Aravalli region) in the west and Deccan Traps in the east, and runs in NE-SW direction, between Delhi in the north to Ahmedabad in the south for about 700 km with a variable width of 10 to 50 km. (Figure 1). The AMR comprises a number of volcano-sedimentary belts, the most prominent of which are the Paleoproterozoic Aravalli Fold Belt (AFB) and Mesoproterozoic Delhi Fold Belt (DFB). Two depositional basins have been described in the NE-SW trending Aravalli Fold Belt which occurs in the central parts of AMR (Roy et al', 1988). The eastern basin which preserves Aravalli Supergroup, comprises a lower mafic volcanic unit, overlain by a sequence of shallow water sediments whereas the western basin is characterized by Jharol Group which is made up of a sequence of deep water sediments and a mafic-ultramafic sequence interpreted as a Proterozoic ophiolite (Sinha-Roy, 1988; Abu Hamatteh et al.' 1994).

The Delhi fold belt having well defined boundaries is constituted by Mesoproterozoic Delhi Supergroup, along with the late/post-orogenic intrusive bodies of granitoids, diorite-tonalite, serpentinite and gabbro-norite-charnockite. The basement rock of the two supergroups, viz., Aravalli and Delhi, is Banded Gneissic Complex (BGC). The Archean BGC is a heterogenous assemblage of sediments, migmatites, granites, pegmatites, aplites and metabasics. In the Geological Survey of India map (Gupta et al.' 1980), the rocks of BGC have been regrouped as Hindoli Group (metagreywacks, basic volcanics and semipelites), Mangalwar complex (mostly gneisses) and Sandmata Complex (mostly granulite facies rocks).

Heron (1953) recognized the Delhi System as a sequence, which unconformably overlies the Aravalli System. According to Singh (1982, 1988), the Delhi basin initially formed in the northeastern part of AMR in Rajasthan, which subsequently extended to the axial zone of the Aravalli Mountains. Heron (1953) proposed a three-fold classification of the Delhi System as follows:

Ajabgarh Series

Alwar Series
Raialo Series
~~~~~~~~~
Pre-Delhi rocks

Heron (1953) also mapped assemblages of marbles and mica schists in regions outside the main Delhi basin and further south, few large bodies of quartzites and coarse-grained marbles within the biotite gneisses in the Mavli region (BGC terrain) and termed them as Delhi outliers. However later on, detailed mapping by Geological Survey of India (Sant and Sharma, 1973; Dutta and Ravindra, 1980 ; Singh 1982, 1988; Singh and Sinha, 1983) conceived that in fact the Delhi outliers are part of the 'Raialo Series'. In order to avoid any confusion, Roy et al' (1988) proposed renaming of this lithostratigraphic unit, as the Rayanhalla Group and placed it at the base of the Delhi Supergroup. He proposed following three-fold stratigraphic classification for Delhi rocks:

Delhi Supergroup	Ajabgarh Group	Dominantly peletic and volcanics
	Alwar Group	Dominantly arenites and volcanics
	Rayanhalla Group	Dominantly carbonate and volcanics
~~~~~~~~~

Various authors, including Gupta et al. (1980) and Sinha-Roy and Gupta (1995) proposed that Delhi Fold Belt should be divided into North Delhi Fold Belt (NDFB) and South Delhi Fold Belt (SDFB) as these are exposed along two sides of a gneissic terrain of Archean age around Ajmer and show several lithological and structural variations. Deb and Sarkar (1990) and Deb et al. (1989, 2002) observed that despite apparent similarities in the rock sequence of NDFB and SDFB as advocated by Roy et al' (1988), there are significant differences in terms of volcanic/sedimentary ratio, nature of mafic-ultramafic rocks, occurrences of carbonaceous and ferruginous rocks of the two belts. Forthermore, the ages of granite plutons which intrude rocks of the NDFB and SDFB are 1500-1700 Ma and about 800 Ma respectively (Chaudhari et al., 1984) provide unequivocal evidence about their division. Deb et al. (1989, 2001) showed that the VMS type ores in the SDFB are about 1.0 Ga, in contrast to the 1.8 Ga ages of the deposits of NDFB. They further recorded that the SDFB along its western fringe is constituted by the volcano-sedimentary lithopackage which hosts the VMS deposits. They named this terrain as Ambaji-Sendra Belt with an assigned age of 1.0 Ga. In SDFB, the terms Alwar and Ajabgarh have been replaced by Gogunda and Kumbalgarh respectively (Gupta et al., 1980). While the SDFB occurs as a linear tract along AMR, the NDFB occupies a wider area comprising Bayana, Alwar and Khetri basins. (Singh ,1988; Raza et al., 2001). The rocks are best exposed in the Alwar basin. The SDFB with extensive mafic volcanism, localized felsic volcanism, argillaceous-arenaceous-carbonate accumulations in successive, elongated basins and conspicuous felsic plutonism is interpreted as an island arc (Deb and Sarkar, 1990).

There are two schools of thoughts regarding the tectonic evolution of DFB viz., single-stage orogenic evolution and diachronous evolution. According to first school, the structural and metamorphic history of rocks of the DFB indicates a single stage orogenic evolution of the entire belts, which have undergone (Tectono) thermal reconstitutions at later periods. Naha, (1983), Roy and Das (1985) and Singh (1985) believe that there is virtually a uniform pattern in the nature of superposed folding and regional metamorphism of rocks in the entire belt and the possible presence of a folded unconformity in the region between Ajmer and Beawar unequivocally speak for a single Delhi basin. They opined that ensialic rifting of the

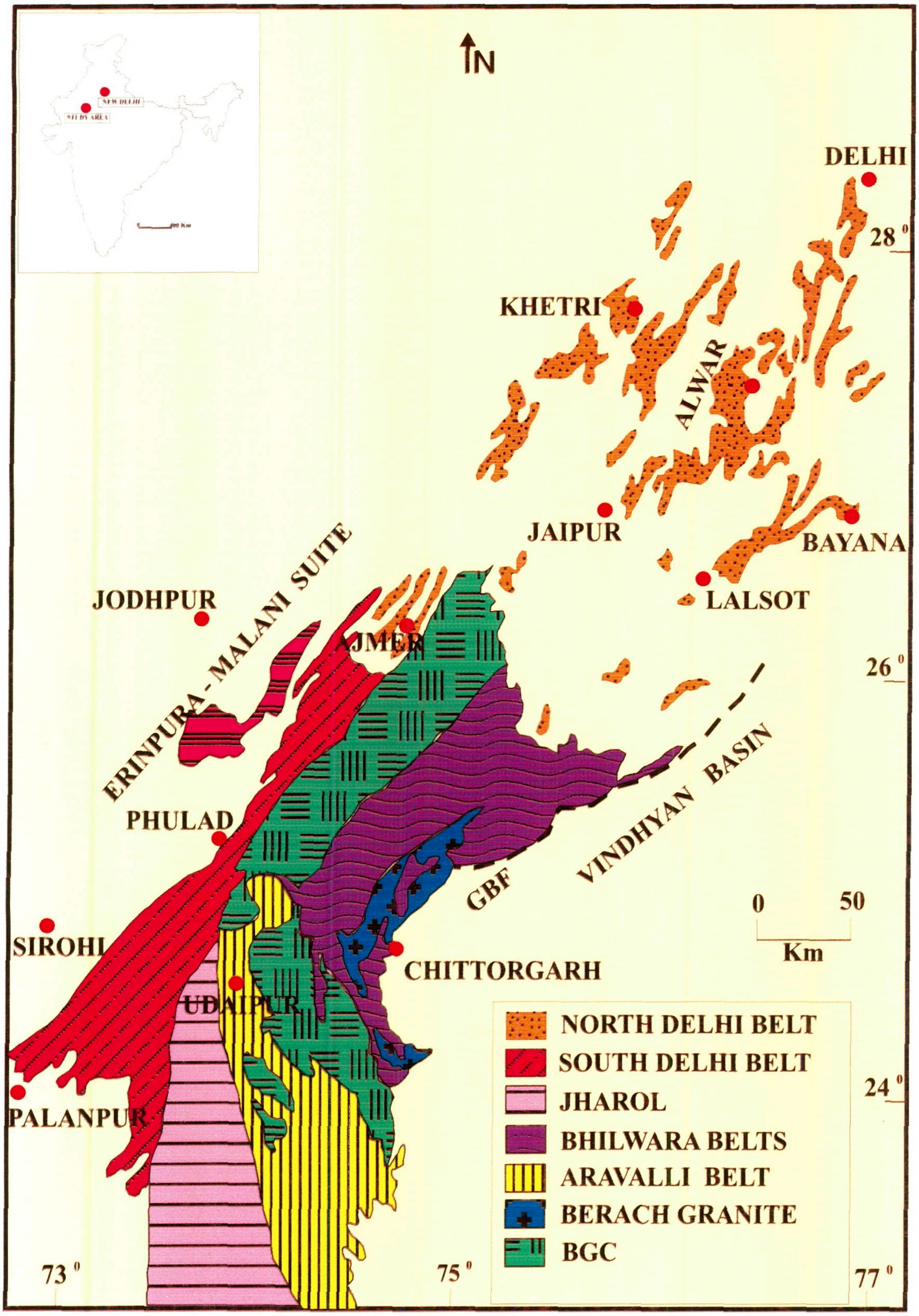


Figure 1. Simplified tectonic map of Aravalli Mountain Range, NW Indian Shield (After Gupta et al, 1980)

pre-Delhi crust took place which paved the way for the deposition of Delhi sediments. The environment of deposition varied from fluvial to various coastal environments including beaches, tidal flats, tidal channels, lagoons and tidal bars (Singh, 1982, 1985). The rocks of the Delhi Supergroup metamorphosed under the low-pressure greenschist and amphibolite facies and records variation in the intensity of deformation. There is an overall increase in the grade of metamorphism and intensity of deformation from east to west and south to north.

Following second thought, Sinha-Roy (1988), Deb and Sarkar (1990), Khan et al. (2005) provided a systematic record of the evolution of DFB and conceived that a Wilson cycle operated in this part of Indian shield during Mesoproterozoic. In their opinion, the Delhi evolution was clearly diachronous with Alwar-Khetri successive rift formation in north Delhi belt preceded the Red Sea type ocean opening in south Delhi belt. The Sambar-Jaipur Dausa transcurrent fault played a dominant role in the opening of north Delhi pull-apart rift basin while it behaved as a transform fault for the ocean opening in south Delhi. The north Delhi rifting was abortive, but the south Delhi basin developed into an oceanic trough.

Gupta et.al. (1991) also advocated the diachronous evolutionary history of the Delhi basin. The authors expressed serious doubt as to the validity of a correlation between the rocks of NDFB and the SDFB by Roy (1988) and Singh (1988). Gupta et al. (1991) used local formational names like Sendra-Barotiya (introduced by Heron), Rajgarh and Bhim in SDFB instead of terminologies like Alwar and Ajabgarh Groups common to NE Rajasthan. They explained that deposition of the stratigraphically equivalent Barotiya, Sendra and Rajgarh formations took place in the first stage which was followed by the deposition of Bhim sediments. These two depositional episodes are separated by atleast one phase of tectonism and granite emplacement. This stratigraphy demonstrates a diachronous evolutionary history of the Delhi

Roy and Jakhar (2002) have discussed the geology of the DFB separately under two different locations, i.e., Alwar-Bayana Basin and main Delhi basin. They opined that the lithological character of the rocks of southern Delhi basin indicate successive deepening of the basin in the westerly direction and thus show younging in that direction. In contrast, rocks of the northern Delhi basin do not show any linear distribution pattern or polarity in terms of younging. However, still there is no acceptable and unified stratigraphic framework of the main Delhi basin and Alwar-Bayana Basin. Therefore, no direct stratigraphic correlation is possible between rocks of these two basins.

The review of the radiometric age data points out that the possibility of the opening and closing of the Delhi basins occurred between 1.7Ga and 1.45Ga respectively and different types of post-orogenic intrusions occurred at 1.00Ga and 0.835 Ga.

Although there is no 'one acceptable-model' for the evolution of DFB, there is a broad causeway that suggests the orogenic evolution of DFB is related to the plate tectonic processes involving rifting, generation of oceanic crust, subduction etc. According to Sinha-Roy and Gupta (1995), during 2.0-1.5 Ga the Aravalli rift developed and formed the Aravalli ocean which closed and subducted towards the east giving rise to the AFB and Sandmata Granulite Complex. At the same time the Delhi rift was initiated due to the Aravalli subduction which developed into an ocean and subsequently closed and subducted towards the west giving rise to the Delhi fold belt during 1.5 to 1.0 Ga. Although the successive rift opening of Aravalli basin is the theme of model visualized by Sinha-Roy and Gupta (1995), there is an obvious difference in detail mainly because of adoption of a distinctly different stratigraphic framework of rocks of the Udaipur sector by the authors. Sinha-Roy and Gupta (1995) adopted a tectonic model of pull-apart basin for the 'isolated linear belts' which was conceived as time-equivalent of the Paleoproterozoic Aravalli Supergroup, infolded into the 'Archean BGC terrain'.

The basal volcano-sedimentary associations developed in some sections of Aravalli succession are typical of the Paleoproterozoic greenstone belts (Paliwal, 1998, Raza and Khan, 1993). The process of greenstone evolution according to Raza and Khan (1993) was aborted after the initial stage of Aravalli basin development. The early tectonic process was subsequently replaced by rifted basin and aulacogen evolution.

LOCATION OF THE STUDY AREA

The Delhi basin extends over a strike length of more than 700 km in NE-SW direction and has a maximum width of 120 km in the north-east Rajasthan. In its north-eastern part, the Delhi basin consists of several structural depositories which received 3-10 km thick volcanic and sedimentary sequences belonging to Delhi Supergroup. The Bayana Basin defines easternmost limit of the great Delhi basin with a 3000m thick metavolcanic and metasedimentary sequence followed by Alwar and Khetri basins from east to west.

The Bayana Basin is located 45 km south-west of Bharatpur city and comes under the revenue jurisdiction of Bayana and Weir tehsils of Bharatpur district, Rajasthan. It is confined between latitudes $26^0 53'$ and $27^0 02'$ north and longitudes $77^0\ 00'$ and $77^0 18'$ east. Bayana is located in a small plain between two hills running more or less parallel to each other near left bank of the Gambhir river. Ancient name of Bayana is 'Sripatha' or 'Sriprastha'. The place has a dry climate with a hot summer, a cold winter and a short monsoon season. Average rainfall is 657.8mm ($25^0 99''$). The land in Bayana is generally fertile and usually flat. The area forming the eastern limit of the Delhi outcrop is connected with National Highway number 11 at Chhokarwara through Bhusawar by a metalled road. Geological formations exposed in this area are Delhi and Vindhyans which are separated by the tapering outcrops of alluvium.

PREVIOUS WORKS AND STRATIGRAPHIC FRAMEWORK

Hacket (1877) was the first geologist to claim some significant contribution to this area by establishing the regional stratigraphy of this part of Delhi basin. Hacket (1881) classified the lithotypes of Bayana hills into five stages under the Alwar series. In Hacket's published map, there is no differentiation between the Delhi System and the Aravalli System (Aravalli series of Hacket), except that the ridges of Alwar quartzites are colored as the Delhi System. He was followed by Heron in 1917. Heron (1953) gave a detailed account of geology of this area in his classic memoir 'The Geology of Central Rajputana' published as the memoir of the

Geological Survey of India, volume 79. Later Banerjee and Singh (1977), Singh (1982, 1984, 1985), Alam and Ahmad (2000) discussed depositional environments and sedimentation pattern from parts of Bayana Basin.

Geologically, the Bayana Basin is composed of around 3000m thick sequence of conglomerates, sandstones, shales, basal volcanic flows and volcanoclastics. The Bayana Basin is bounded by pre-Delhi rocks on its southern and south-eastern sides (Figure 2). The infillings of this basin are represented by metasedimentaries and metavolcanics belonging to Delhi Supergroup with faulted contact with pre-Delhi rocks along its south-eastern fringe. Stratigraphically, Bayana Basin has been subjected to a three-tier classification, mainly on the basis of two unconformities. Each of these three units, having the status of a group, has been further sub-divided into formations and member in conformity with the 'Code of Stratigraphic Nomenclature of India' (Anon 1971). The stratigraphic scheme erected by Singh (1982) for the Bayana Basin is shown in the Table 2. The oldest unit of Hacket (op. cit.) i.e. Nithar stage has been sub-divided into three parts. All three parts have been assigned the status of a formation and termed as Nithar, Jahaj-Govindpura volcanics and Jogipura formations respectively. The Jahaj-Govindpura volcanics show thinning towards east and west and along with the Nithar Formation, and completely disappear beyond Khareri ($26^0 56'$: $77^0 11'$) in the east and Nithar ($26^0 58'$: $77^0 02'$) in the west (Figure 2). The Jogipura Formation shows successive overlap onto these two formations and comes in juxtaposition with the pre-Delhi rocks, 700 m west of Aund ($26^0 58'$: $77^0 01'$) in the west and near Madpur ($26^0 52'$: $77^0 13'$) in the east (Figure 2). This overlapping, together with the boulder conglomerate at the base of Jogipura Formation showing pebbles of the tuff and basalt indicate an unconformity between Jahaj-Govindpura volcanics and the Jogipura Formation. On the basis of this unconformity and the correlation of these formations with identical formations in other parts of the Delhi basin, the Nithar Formation and Jahaj-Govindpura volcanics have been put into the Raialo Group while the Jogipura Formation along with younger Badalgarh , Bayana and Damdama formations have been incorporated into the Alwar Group.

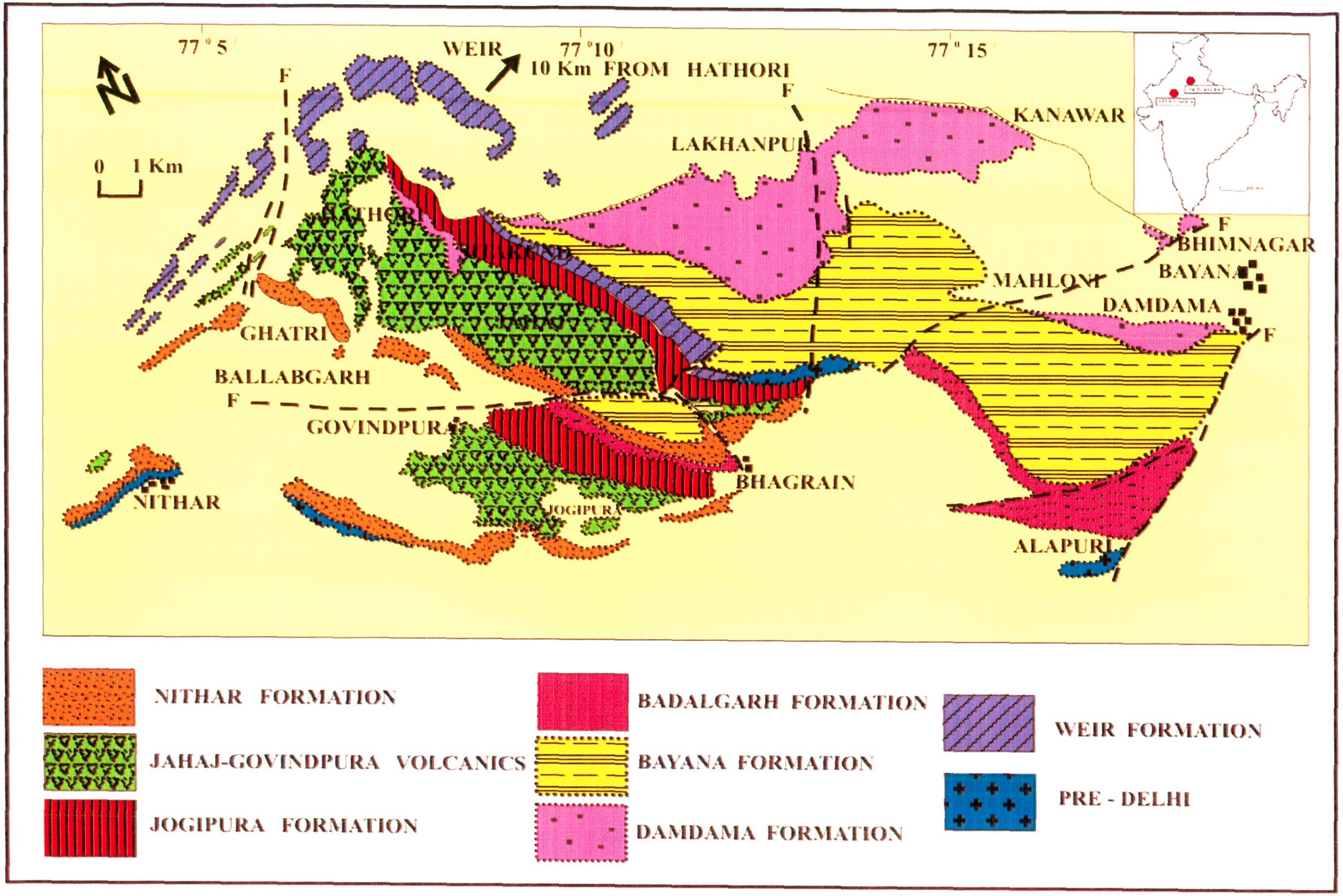


Figure 2. Geological map of Bayana Basin,Rajasthan (After Singh 1982)

Table 1. The Precambrian stratigraphy of NW Indian Shield

Heron (1953)		Gupta et.al. (1997)		Roy and Jakhar (2002)
Malani series Erinpura granite Delhi Outlier		Proterozoic-III	Marwar Supergroup Malani suite Erinpura granite and gneiss Vindhyan Supergroup	Marwar Supergroup Malani group=Sindreth Group (780-680 Ma) Granite of Erinpura,Pali,etc.835 Ma Sirohi Group Intrusion of gabbro,diorite (1000 Ma)
Delhi System	Ajabgarh series Alwar series Raialo series	Delhi Supergroup 2000-740 Ma Proterozoic-II	Punagarh Group=Sindreth Group SirohiGroup=Sendra,Ambaji granite (ca. 800 Ma) Kumbhalgarh =Ajabgarh Group Gogunda Group=Alwar group	Synorogenic granite (1400 Ma) **Delhi Supergroup**
Aravalli System		Aravalli Supergroup (2500-2000 Ma) Proterozoic-I		Darwal granite (1850 Ma) Aravalli Supergroup
Banded Gneissic Complex (BGC)		Bhilwara Supergroup Archean		Untala,Ahar,Berach granitoids (2500 Ma) Mewar gneiss (Heron's BGC) (2600-3300 Ma)

The Alwar Group of rocks was deposited in a prograding beach environment resulting in gradual pinching of the beds towards west. The younger three formations of this group die out north of Sitakund ($26^0 59'$: $77^0 07'$) and the lowermost formation shows discontinuous outcrops west of Hathori ($26^0 00'$: $77^0 06'$). The lowermost bed of Weir stage again overlaps the younger three formations of the Alwar Group and comes in contact with Jogipura Formation in north of Hathori warranting its placement in the Ajabgarh Group (Figure 2). The Weir stage of Hacket has been subdivided into two units, each having the status of a formation. The original terminology has been retained for the younger unit while the older one has borrowed its name (Kushalgarh Formation) from the Alwar Basin (Singh,1985).

AIM AND SCOPE OF THE STUDY

The present work aims to study in detail the lithofacies, texture, detrital mineralogy and diagenesis of Delhi Supergroup sandstones of Bayana Basin. It is further aimed to interpret the provenance and depositional environment of the Bayana Basin.

During fieldwork, special attention was paid to study the nature of sedimentary structures, like cross-bedding, lamination, ripple marks etc. Lithosections were prepared on the basis of field data and lithofacies were identified. Thin sections of the sandstone samples were made and used for the petrographic study. The textural attributes of the sandstones, such as size, roundness and sphericity were studied with a view to interpret the provenance and estimating the influence of texture on the detrital modes and petrofacies. Bivariant plots are made to find out the interrelationship of various textural attributes. Statistical parameters of grain size are computed with the help of cumulative frequency curves and the methods after Folk (1980).

Detrital mineralogy of the sandstones, including lighter and heavy mineral fractions is studied for the purpose of petrographic classification of the sandstones and interpretation of their provenance. Classification schemes of Folk (1980) based on composition of detrital constituents and that of Dickinson (1985) based on the tectonic setting of the provenance are employed.

An attempt has been made to study the diagenetic history of the sediments. The diagenetic history includes compaction, porosity reduction and cementation. The study is based on examination of thin sections and includes various diagenetic aspects, such as types of grain contacts, porosity reduction and types of cement.

Table 2. Stratigraphic Succession of Delhi Supergroup in the Bayana Basin (after Singh, 1982)

Group	Formations in Bayana Basin	Member	Thickness	Formations in Alwar sub-basin
Ajabgarh	Weir Kushalgarh		340 m 100 m	Seriska Kushalgarh
		Disconformity		
	Damdama	Lakhanpur sandstone	240 m	Pratabgarh
		Kanawar quartzite	550 m	
		Umraind conglomerate	870 m	
Alwar	Bayana	Mahloni quartzite	880 m	
		Mor Talab quartzite	650 m	Kankwarhi
	Badalgarh	Alapuri quartzite	185 m	
		Bhagrain sandstone	100 m	Rajgarh
	Jogipura	Quartzite	275 m	
		Sita conglomerate	100 m	
		Unconformity		
Raialo	Jahaj-Govindpura volcanics	Upper Middle	1000 m	Tehla Serrate quartzite
	Nithar	Lower Quartzite Conglomerate	2000 m	Dogeta
		Unconformity		
Pre-Delhi formation	Aravalli Supergroup			

Lithostratigraphy

CHAPTER - II

LITHOSTRATIGRAPHY

The stratigraphic sections of the Delhi Supergroup sandstones in Bayana Basin were measured at several localities in the study area. Ten sections were selected for this study which mainly consists of sandstones, in places interbedded with conglomerates and shales. None of the sections show thickness more than 85 meters. The Lithostratigraphic details of the measured sections are as follows:-

Nithar Formation

Nithar Village

Lithostratigraphic section (Figure 3) measured near Nithar village is 31m thick. The Lithostratigraphic succession is as follows:

26.0-31.0m: Thick-and-thin bedded sandstones. Presence of Herring-bone cross-beddings (Photo 1), tabular cross-beddings and ripple marks.

21.5-26.0m: Medium-grained, hard and compact, thick-bedded sandstones. Laminations are common.

19.5-21.5m: Thick-bedded clast-supported conglomerates (Photo 2).

18.5-19.5m: Medium-grained pinkish, hard and compact sandstones.

16.5-18.5m: Brownish, thick-bedded, clast-supported conglomerates. Pebbles of vein quartz, quartzite, jasper.

14.5-16.5m: Thick-bedded, pink, medium to fine-grained sandstones.

12.5-14.5m: Red shale.

10.5-12.5m: Pink, compact and hard, thick-bedded sandstones.

10.0-10.5m: Red shale.

7.0-10.0m: Thick-and-thin bedded, pink, medium-grained sandstones. Laminations are common.

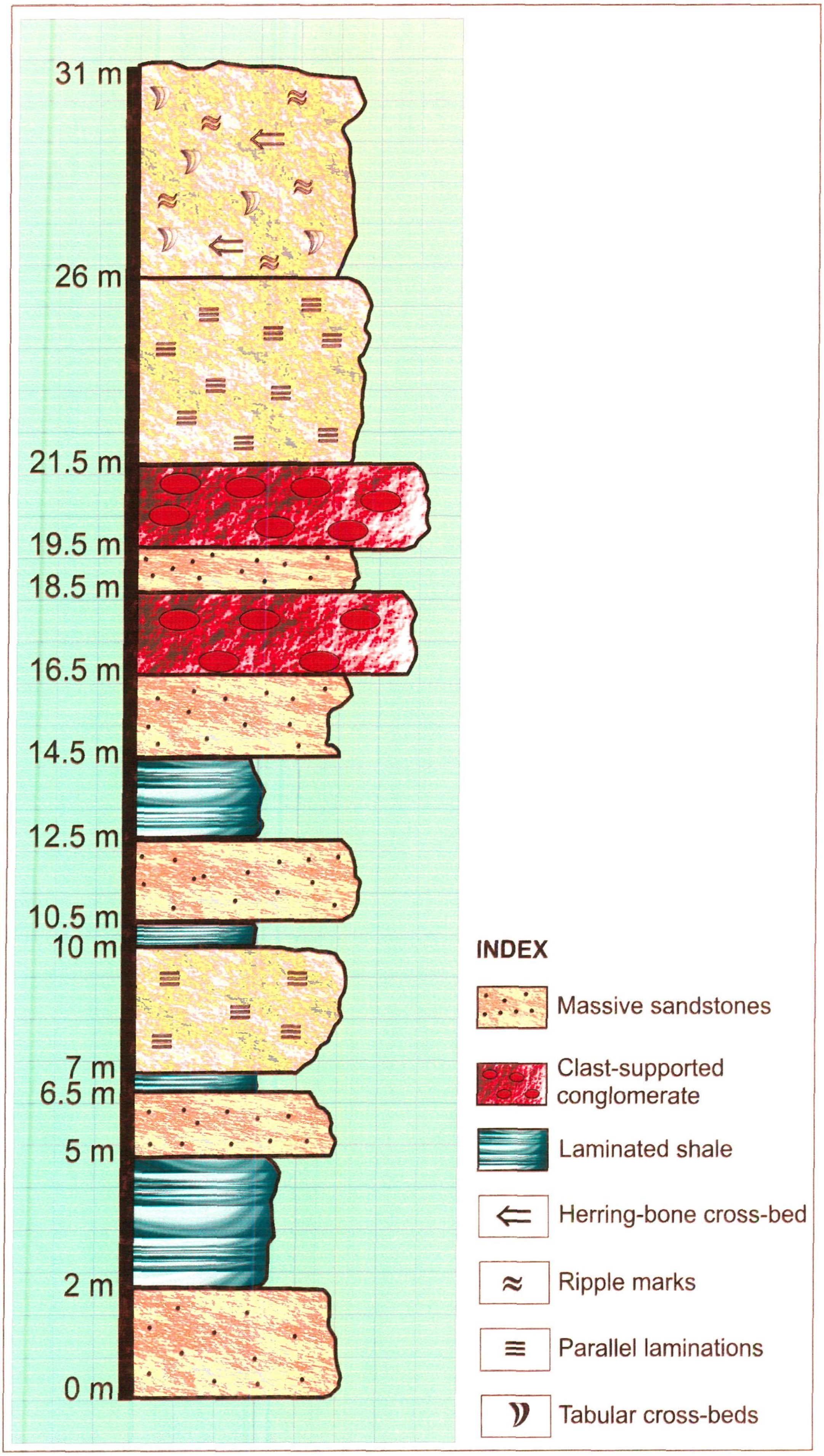


Figure 3. Lithostratigraphic section of Nithar Formation

Photo 1. Field photograph showing Herring-bone cross-bedded sandstones in Nithar Formation

Photo 2. Field photograph showing Clast-supported conglomerate of Nithar Formation

6.5-7.0m: Red shale.

5.0-6.5m: Medium to fine-grained, light pink, hard and compact sandstones.

2.0-5.0m: Red shale

0.0-2.0m: Thick-bedded, medium-grained, pink sandstones.

Jahaj-Govindpura Volcanic Formation

Hathori village

Lithostratigraphic section (Figure 4) measured near Hathori village is 29 m thick. The section has the following sequence:

26.0-29.0m: Laminated, medium to fine-grained, hard and compact, pebbly sandstones. Tabular cross-beds and parallel laminations are present. Presence of irregular bedding.

23.0-26.0m: Thick-bedded tuffacious sandstones.

21.0-23.0m: Thick-bedded tuffacious sandstones.

19.0-21.0m: Pebbly, pink, medium to fine-grained tuffacious sandstones.

18.0-19.0m: Medium to fine-grained tuffacious sandstones containing spatter and agglomerates (Photo 3).

9.0-18.0m: Medium to fine-grained, dark gray, compact and hard tuffacious sandstones.

4.0-9.0m: Dark gray tuffacious sandstones, presence of bomb (Photo 3).

1.0-4.0m: Thick-bedded, dark gray tuffacious sandstones, presence of bomb.

0.0-1.0m: Dark gray, medium-grained, massive, hard and compact sandstones.

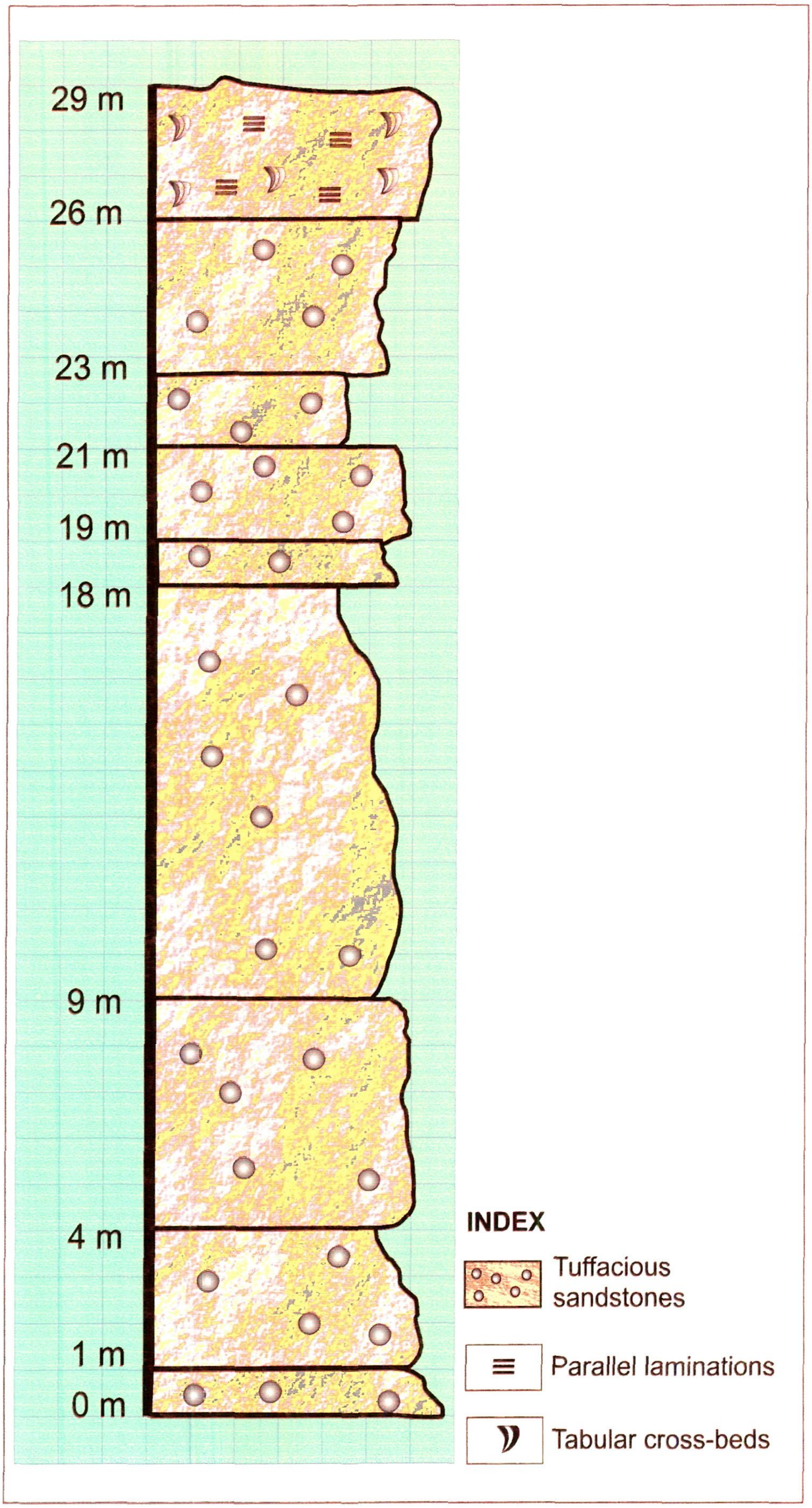


Figure 4. Lithostratigraphic section of Jahaj-Govindpura volcanic Formation

Jogipura Formation

Sitakund village

A lithostratigraphic section (Figure 5) is measured near Sitakund village. The measured section is 28 m thick and shows the following sequences:

33.5-35.5m: Thick-bedded, light pink, medium-grained sandstones. Ripple marks are abundant.

31.5-33.5m: Thick-bedded, brown colored, matrix supported conglomerates. Pebbles of vein quartz and quartzite.

27.5-31.5m: Thick-bedded, medium-grained sandstones. Abundant ripple marks.

24.5-27.5m: Thick-bedded, medium-grained, pink sandstones. Pebbles of vein quartz, basic rocks, maximum clast size are 16 cm. Tabular cross- beddings.

23.5-24.5m: Medium-grained, compact and hard, pebbly sandstones. Pebbles of vein quartz, quartzite. Size of pebbles decreases upward.

18.5-23.5m: Medium-grained, pink colored sandstones. Absence of pebbles. Laminations are common.

16.0-18.5m: Medium-grained thick-bedded sandstones. Mud cracks and asymmetrical ripple marks.

13.0-16.0m: Thick-bedded, pink, medium-grained sandstones. Interference ripples (Photo 4).

12.0-13.0m: Thick-bedded, matrix supported, brownish to black conglomerate. Pebbles of vein quartz, quartzite. Pebbles are oriented in particular direction (Photo 5).

11.0-12.0m: Thick-bedded, pink sandstones with pebbles of vein quartz. Asymmetrical ripple marks.

9.0-11.0m: Conglomerate containing pebbles of vein quartz, quartzite.

8.0-9.0m: Reddish brown, hard and compact, thick-bedded sandstones.

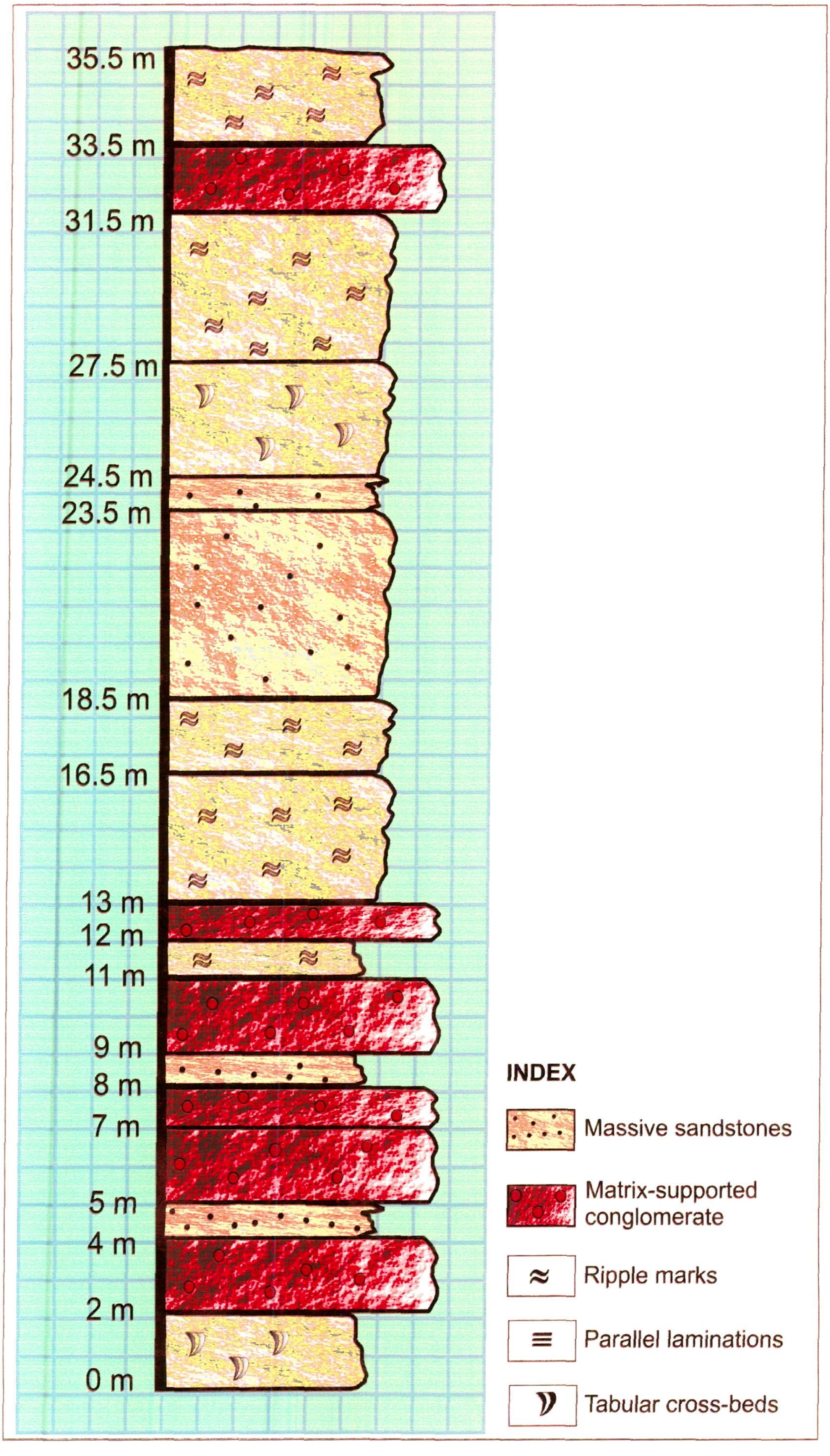


Figure 5. Lithostratigraphic section of Jogipura Formation

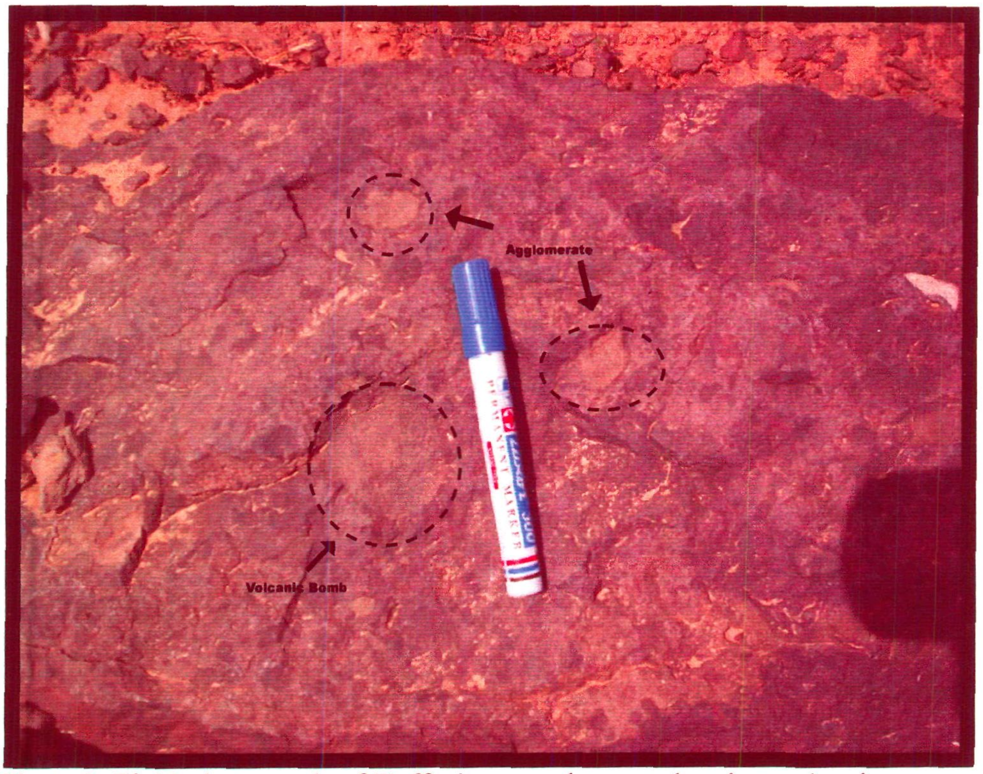


Photo 3. Field photograph of Tuffacious sandstones showing volcanic bombs & agglomerates in Jahaj-Govindpura volcanic Formation.

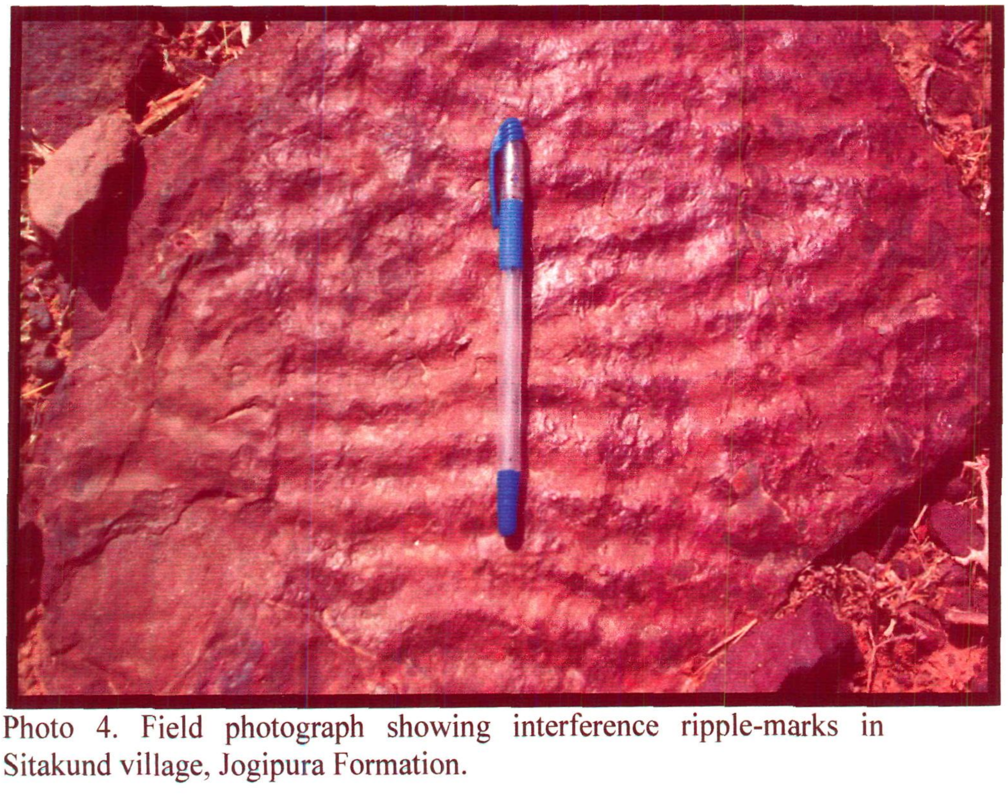


Photo 4. Field photograph showing interference ripple-marks in Sitakund village, Jogipura Formation.

Photo 5. Field photograph showing preferred orientation of pebbles in Sitakund village, Jogipura Formation.

7.0-8.0m: Matrix supported conglomerate with pebbles of vein quartz and quartzite.

5.0-7.0m: Brownish to black, hard and compact, matrix supported conglomerate. Pebbles of vein quartz. Pebbles are arranged in definite direction.

4.0-5.0m: Pink, hard sandstones. Laminations present.

2.0-4.0m: Hard and compact, matrix supported conglomerate, brown to black in colour. Pebbles of vein quartz, jasper and maximum size of pebbles is 80 mm. Pebbles are oriented in one direction.

0.0-2.0m: Medium-grained, reddish brown, cross-bedded sandstones. Pebbles of vein quartz and quartzite. Tabular cross-bedding are common.

Badalgarh Formation

Bhagrain village

A 16 m thick lithostratigraphic section (Figure 6) is measured near Bhagrain village. Sequences of bed from the top to the bottom are as follows:-

11.5-16.0m: Medium to coarse-grained, light yellow, massive sandstones.

10.5-11.5m: Thick-bedded, medium-grained, yellow sandstones. Tabular cross-beddings (Photo 6).

9.0-10.5m: Medium to coarse-grained sandstones. Large scale cross-beddings.

5.5-9.0m: Thinly bedded, medium-grained, pink, hard sandstones. Tabular cross-bedding.

4.0-5.5m: Medium to coarse, pink, hard and compact sandstones.

2.0-4.0m: Pinkish white, hard and compact, laminated sandstones. Medium-grained. Tabular cross-beddings are abundant.

1.0-2.0m: Thick-bedded, pink to white, coarse-grained sandstones. Tabular cross-beddings.

0.0-1.0m: Thick-bedded, medium to coarse-grained, hard and compact. Finely laminated. Tabular cross-bedded, inclination angle of cross-bed is 22^0.

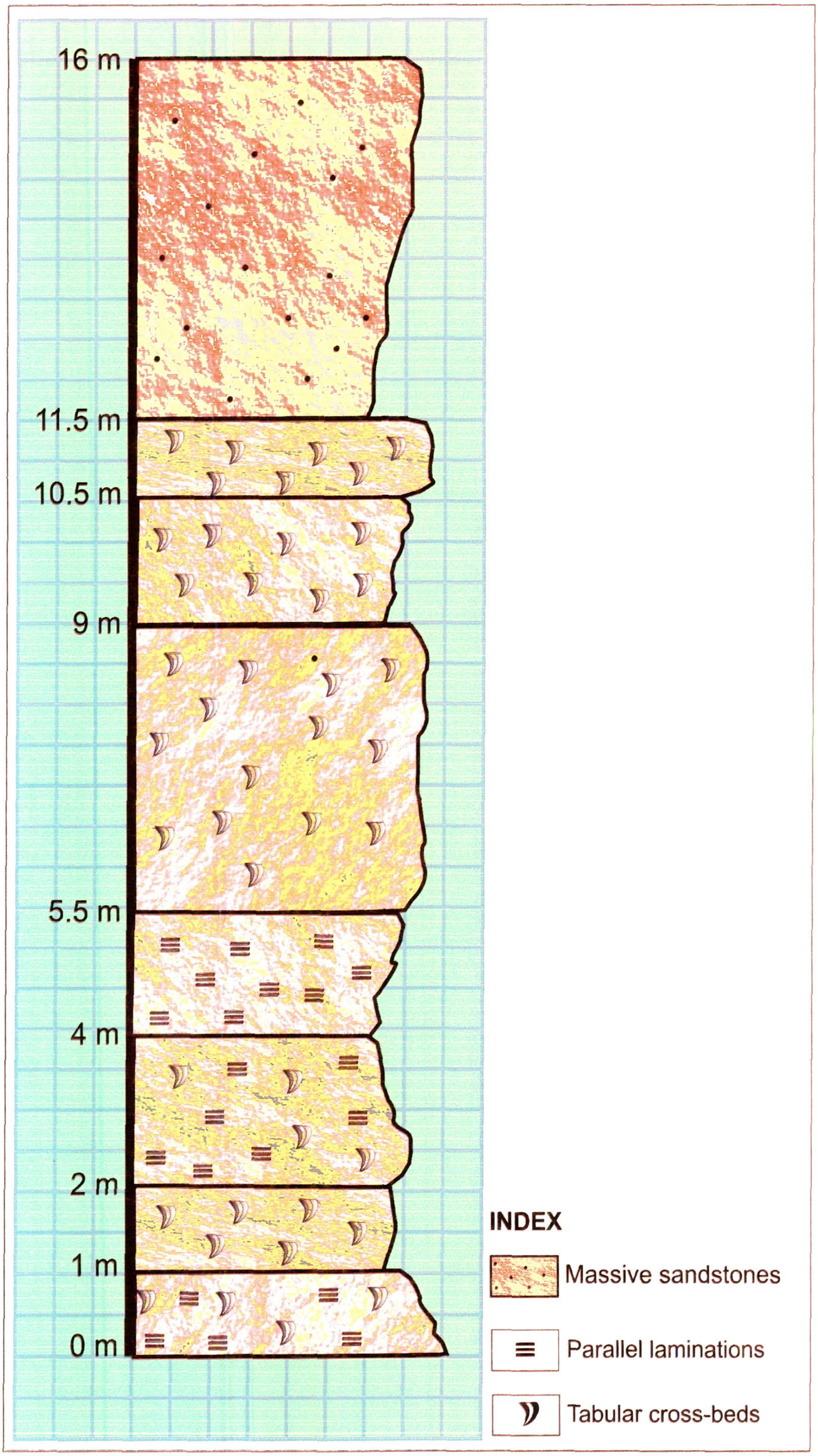


Figure 6. Lithostratigraphic section of Bhagrain locality of Badalgarh Formation

Alapuri village

Lithostratigraphic section (Figure 7) of 23 m thickness is measured near Alapuri village. The section shows following sequences:

14.0-23.0m: Thick-bedded, fine-grained, light pink, massive sandstones.

12.0-14.0m: Thick-bedded, fine-grained, laminated sandstones (Photo 7).

11.0-12.0m: Thick-bedded, fine-grained sandstones.

9.0-11.0m: Thick-bedded, fine-grained sandstones, tabular cross-bedded.

5.0-9.0m: Thick-bedded, fine-grained, milky white massive sandstones.

4.0-5.0m: Coarse-grained, brown, hard sandstones. Tabular cross-beddings.

3.0-4.0m: Fine-grained, white sandstones.

2.5-3.0m: Brown, hard, coarse-grained sandstones. Tabular cross-beddings.

1.5-2.5m: Thick-bedded, fine-grained, white sandstones.

0.5-1.5m: Coarse-grained soft, pink sandstone. Tabular cross-beddings.

0.0-0.5m: Medium to fine-grained, massive, thinly bedded, white sandstone.

Bayana Formation

Bhimnagar village

Lithostratigraphic section (Figure 8) measured near Bhimnagar village is 20.2m thick. Successions in the section are as follows:

19.2-20.2m: Gritty, pink, massive sandstones.

16.2-19.2m: Medium-grained laminated, pink sandstone.

14.7-16.2m: Medium to fine-grained, laminated sandstone, trough cross-beddings.

12.7-14.7m: Laminated, medium-grained, pink sandstones.

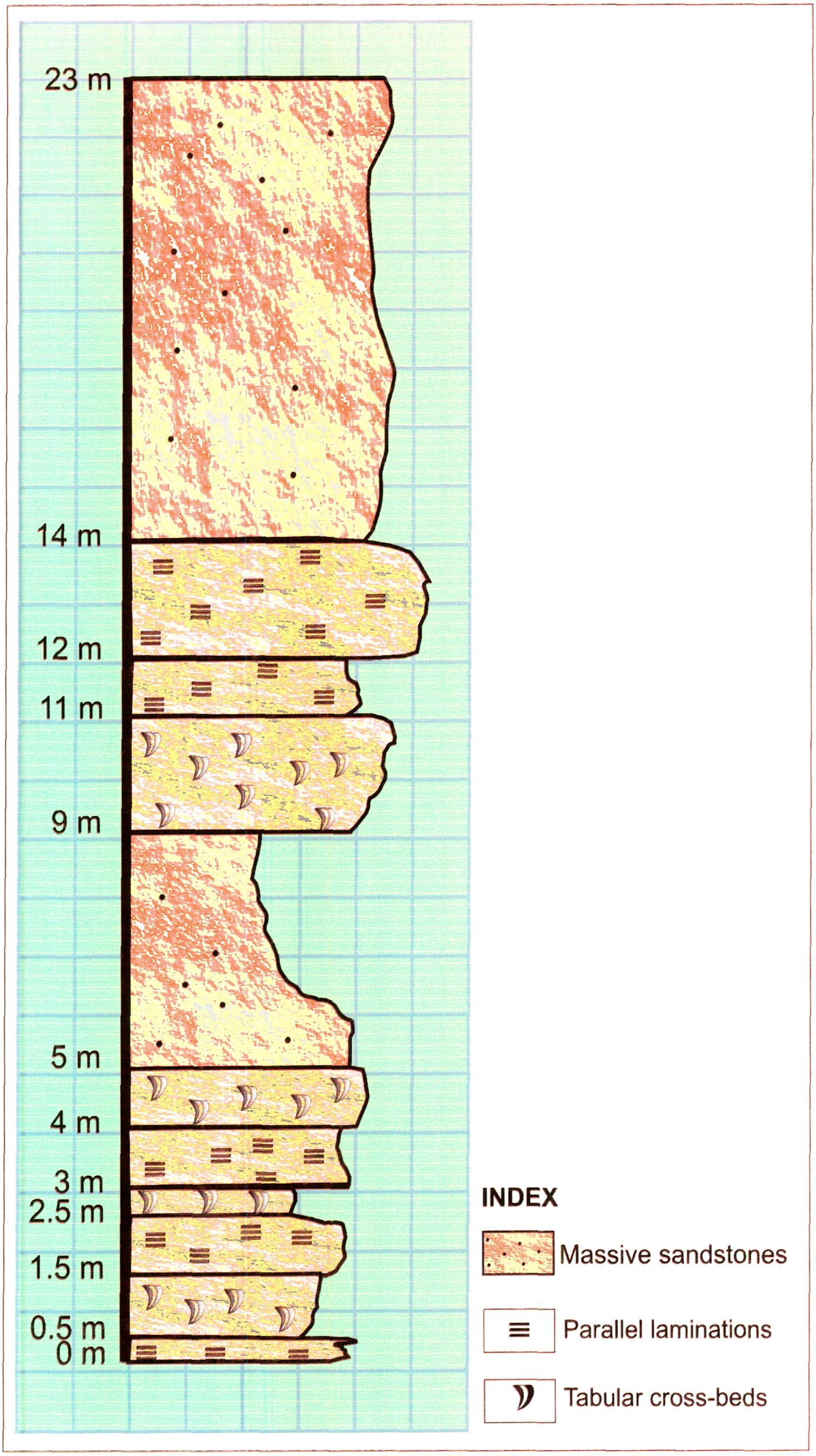


Figure 7. Lithostratigraphic section of Alapuri locality of Badalgarh Formation

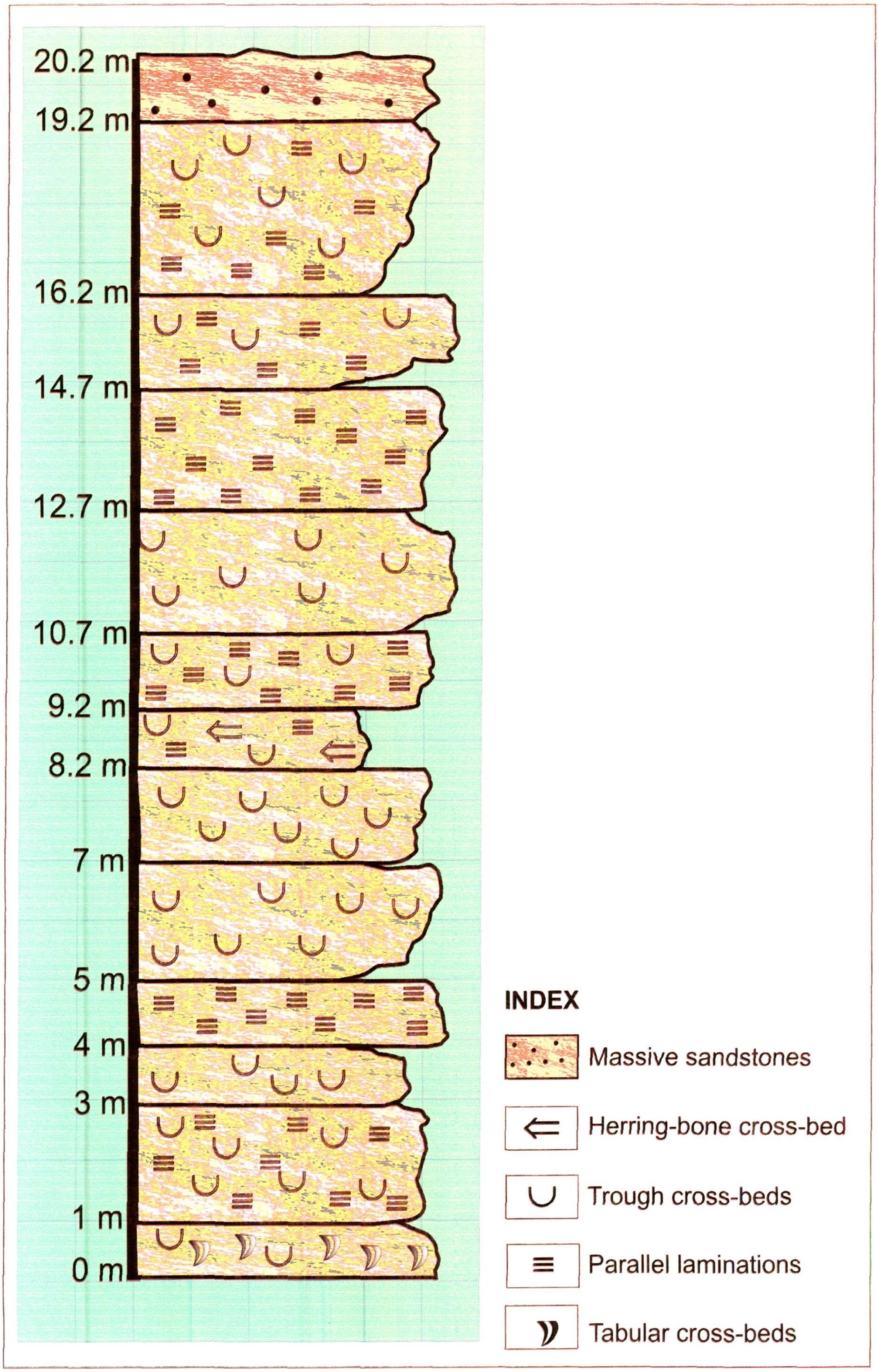


Figure 8. Lithostratigraphic section of Bhimnagar locality of Bayana Formation

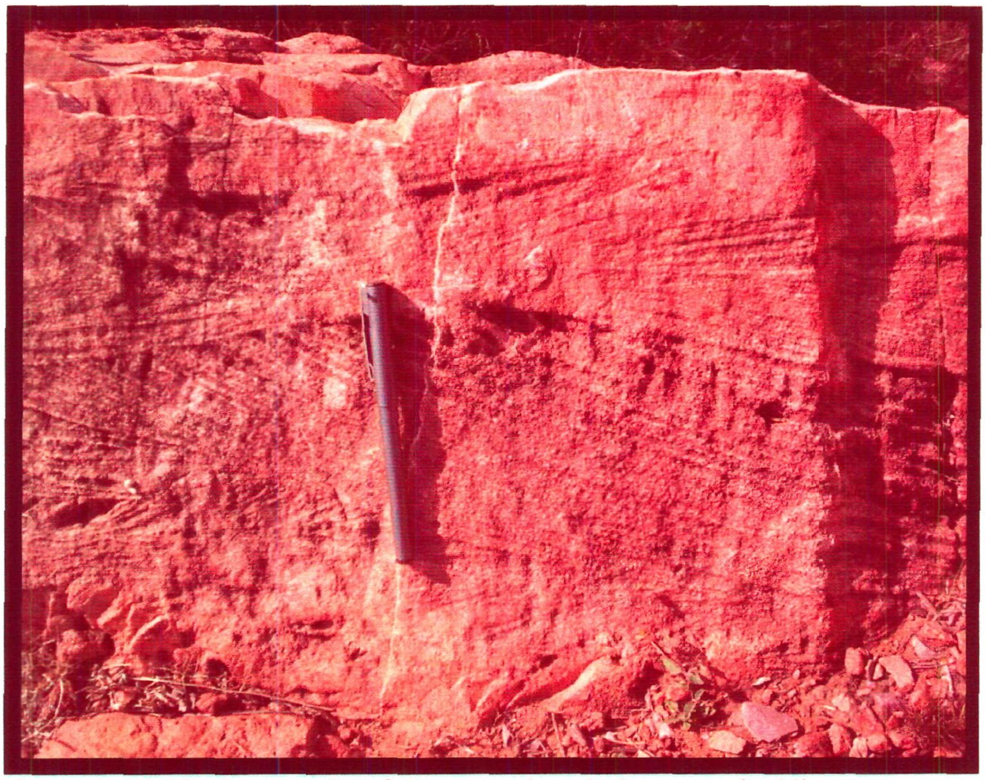


Photo 6. Field photograph of Large-scale tabular cross-beddings, Bhagraine village, Badalgarh Formation.

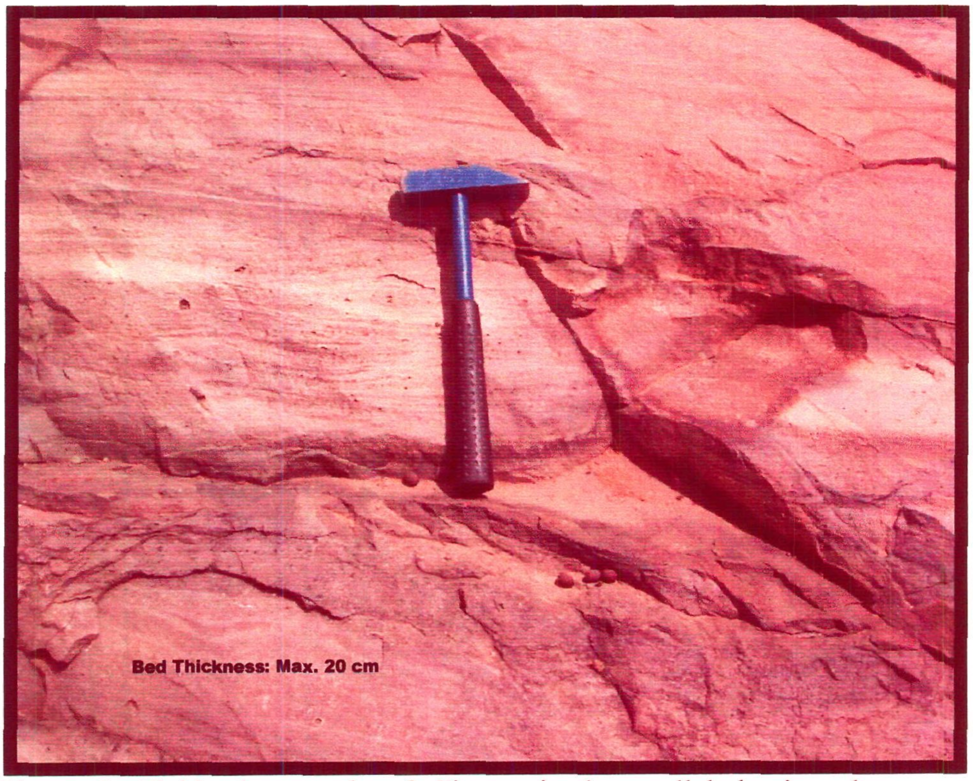


Photo 7. Field photograph of Fine-grained, parallel laminated sandstones of Alapuri village, Badalgarh Formation.

10.7-12.7m: Medium to fine-grained, pink sandstone. Large scale trough cross-bedding. The cross beds are in co-sets.

9.2-10.7m: Medium to fine-grained pink sandstones. Large scale trough cross-beddings at the lower and upper parts. Middle part is laminated. Distorted lamination is seen (Figure10, Photo 8). Trough cross-beds are in co-sets.

8.2-9.2m: Pink sandstones having co-sets of trough cross-beddings and herring-bone cross-beddings. Laminations are common in the lower part.

7.0-8.2m: Medium to fine-grained pink sandstones. Co-sets of trough cross-beddings (Figure 9). Thickness of cross-bed is 40 cm.

5.0-7.0m: Medium to fine-grained, pink, soft, trough cross-bedded sandstones. Co-sets of trough cross-beds.

4.0-5.0m: Medium to fine-grained, pink, laminated sandstones.

3.0-4.0m: Medium to fine-grained, pink, soft, cross-bedded sandstones. Large scale trough cross-beddings are common.

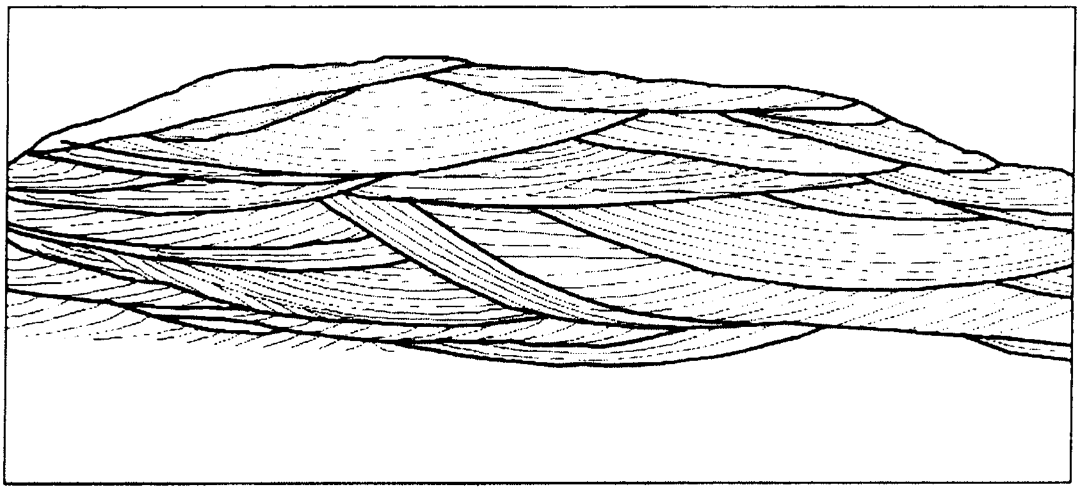


Figure 9. Co-sets of trough cross-beddings in Bhimnagar, Bayana Formation

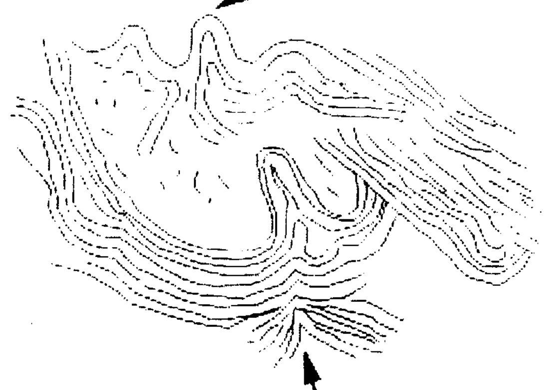


Figure 10. Distorted laminations in Bhimnagar, Bayana Formation

1.0-3.0m: Medium to fine-grained, light pink, laminated sandstones. Large scale trough cross-beddings are common.

0.0-1.0m: Medium to fine-grained, light pink, cross-bedded sandstones. Large scale tabular and trough cross-beddings are common.

Near Bayana Town

A lithostratigraphic section (Figure 11) is measured near Bayana town. The measured section is 85 m thick and comprises sandstones and conglomerate. The section has the following sequences:

79.0-85.0m: Purple, medium to coarse-grained, hard and compact, cross-bedded sandstones intercalated with 5 cm thick bed of conglomerate. Large scale tabular cross-beddings and laminations are common. Inclination angle of cross-bed is 50^0.

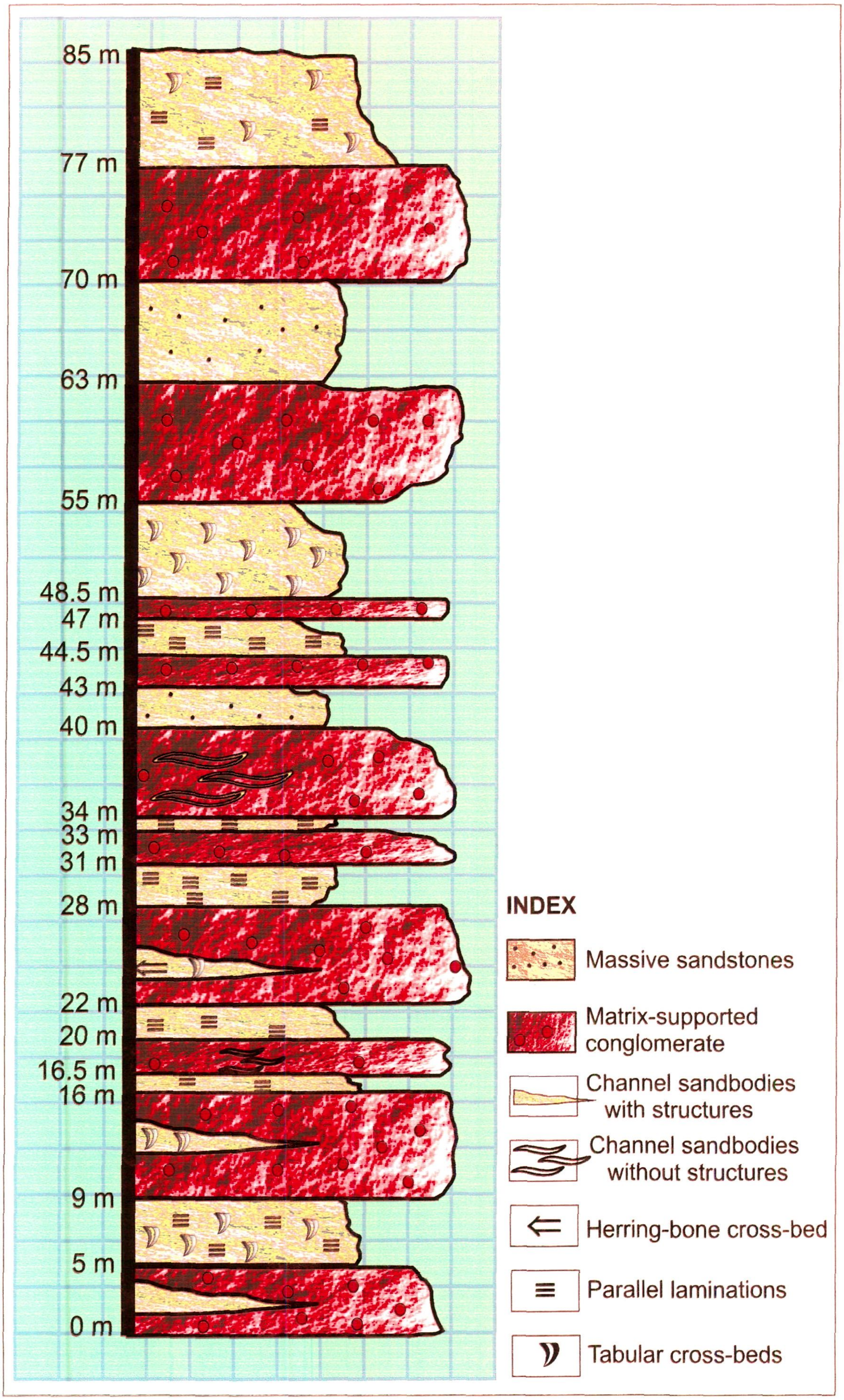


Figure 11. Lithostratigraphic section near Bayana Town, Bayana Formation

70.0-79.0m: Reddish brown, hard and compact, matrix-supported conglomerate. The conglomerate is intercalated with sandstones.

63.0-70.0m: Massive, hard and compact sandstones. Highly deformed.

55.0-63.0m: Brown to black, matrix supported, hard and compact conglomerate (Photo 9). Clast sizes decreases upward.

48.0-55.0m: Medium to fine-grained, light brown, hard and compact cross-bedded sandstones. Wavy beddings.

47.0-48.5m: Matrix supported conglomerate intercalated with sandstones (Photo 10).

44.5-47.0m: Medium to fine-grained, hard and compact, purple, laminated sandstones.

43.0-44.5m: Matrix supported, hard to compact conglomerate. The clast size within conglomerate decreases upward.

40.0-43.0m: Medium to fine-grained, pink, hard and compact sandstones. Lower bounding surfaces of sandstones show impression of ripples. A 10 cm thick conglomerate unit lies within sandstones bed.

34.0-40.0m: Reddish brown, matrix supported, compact and hard conglomerate. The presence of channel sandstone body which consist of clasts of conglomerate. Channel axis is N 220^0.

33.0-34.0m: Medium to fine-grained, light purple, compact, laminated sandstones.

31.0-33.0m: Reddish brown, matrix supported, hard and compact conglomerate. Conglomerates interbed with 4 to 8 cm thick sandstones bodies.

28.0-31.0m: Light purple, medium to fine-grained, hard and compact, laminated sandstones. Wavy bedding is common.

22.0-28.0m: Matrix supported conglomerate intercalate with 10-15 cm thick sandstones body. Channel sandstone body is showing mild cracks. A large scale

Photo 8. Field photograph of Distorted laminations in sandstones of Bhimnagar locality, Bayana Formation.

Photo 9. Field photograph of Matrix-supported conglomerate near Bayana Town, Bayana Formation.

tabular cross- beddings, herring-bone cross-beddings and laminations are common in the lower part. Axis of the channel sandstone body is N350^0. It consists of 2 -6 cm subangular gray-white quartzite clasts.

20.0-22.0m: Medium to fine-grained, light purple, compact, laminated sandstones. Wavy contact is observed.

16.5-20.0m: Blackish brown, matrix supported conglomerate. Hard and compact. A channel sandstone body is present in the conglomerate which is 40 cm. Tabular cross-beddings are common within the sandstone body. Inclination angle of cross-beds range from 25^0 to 49^0.

16.0-16.5m: Medium to fine-grained sandstones, purple, compact and hard. Laminations are common. Presence of wavy contacts.

9.0-16.0m: Blackish brown, compact and hard, matrix supported conglomerate. The maximum size of the individual clast is 2 cm. wavy beddings are common.

5.0-9.0m: Medium to fine-grained, light purple, compact, cross-bedded sandstones. Laminations are common..

0.0-5.0m: Blackish brown, hard and compact, matrix supported conglomerate. The conglomerates contain scattered pebbles of maximum size of 2.5 cm. Large scale tabular cross-beddings and wavy beddings are common. Inclination angles of cross-beds range from 15^0 to 49^0.

Damdama Formation

Umraind village

The lithostratigraphic section (Figure 12) measured near Umraind village is 32 m thick and has the following sequences:

30.5-32.0m: Medium to coarse-grained, light yellow, pebbly sandstones. Cross-beddings are common. Inclination angle of cross- bed is 26^0.

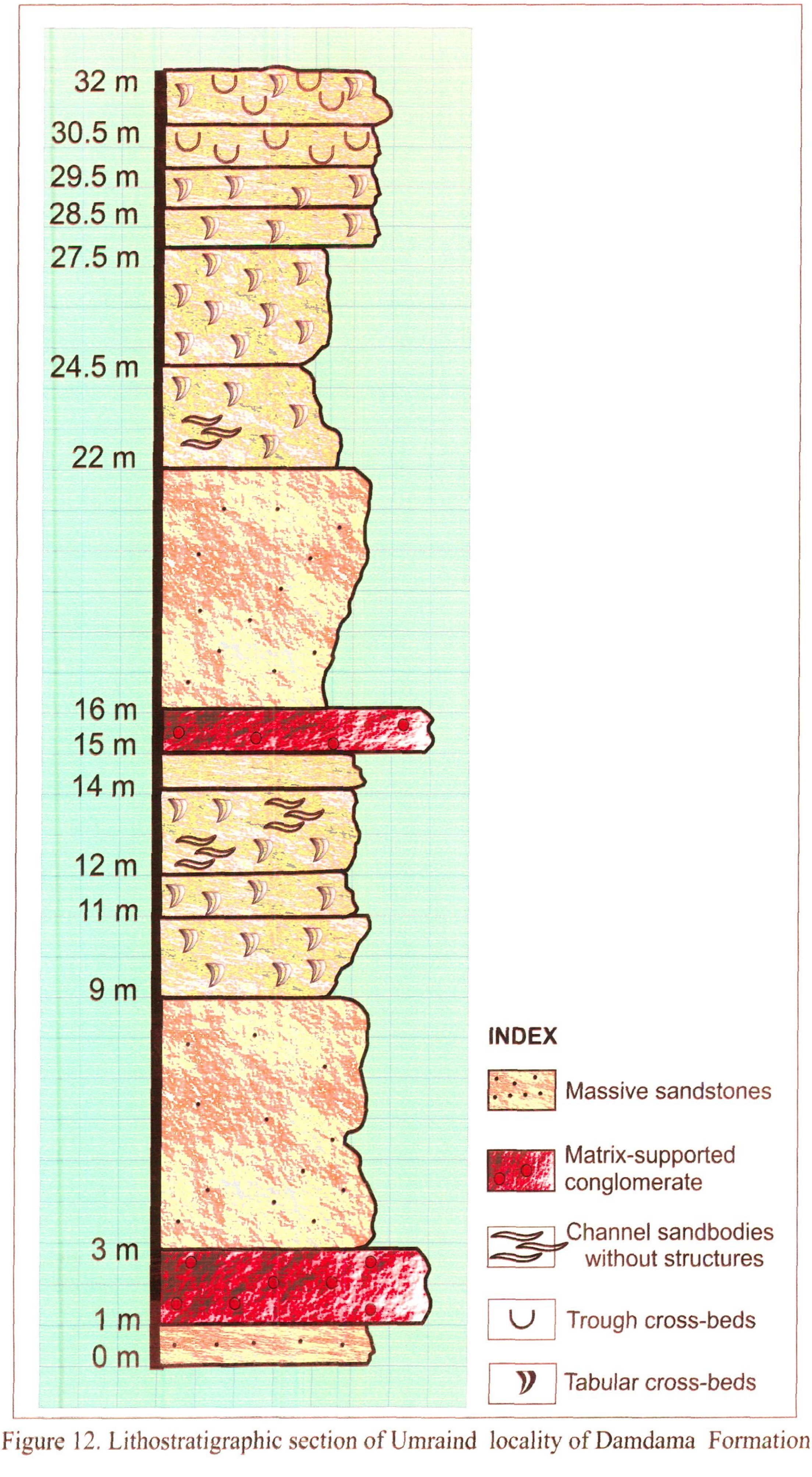


Figure 12. Lithostratigraphic section of Umraind locality of Damdama Formation

29.5-30.5m: Light brown, medium-grained sandstones, trough cross-bedded. Occasional swaley-type trough cross-beddings.

28.5-29.5m: Medium-grained pebbly sandstones, light brown in color. Tabular cross-beddings (Photo 11).

27.5-28.5m: Pebbly sandstones, medium-grained, light yellow, hard and compact. Tabular cross-beddings.

24.5-27.5m: Medium-grained, light yellow, pebbly sandstones. Tabular cross-beddings.

22.0-24.5m: Light brown medium-grained pebbly sandstones. Upper part of the bed shows tabular and hummocky type cross-beddings.

16.0-22.0m: Gritty sandstones, light yellow to brown colored.

15.0-16.0m: Brownish to black, matrix supported conglomerate. The maximum size of clasts range between 16 to 32 mm.

14.0-15.0m: Pebbly sandstones.

12.0-14.0m: Pebbly cross-bedded sandstones, tabular cross-bedding in the upper and lower part of the bed. Middle part of the bed contains channel sand bodies.

11.0-12.0m: Gritty sandstones. Tabular cross-bedded, inclination angle of cross-bed is 44^0.

9.0-11.0m: Course to medium-grained, light brown pebbly sandstones. Tabular cross-bedded.

3.0-9.0m: Gritty sandstones.

1.0-3.0m: Poorly sorted, light brown, matrix supported conglomerate. The maximum size of the clasts goes upto 18 cm. The predominant phenoclasts are vein quartz, quartzite, and basic rocks.

0.0-1.0m: Thick-bedded, pebbly to gritty sandstones. Light brown in colour.

Photo 10. Field photograph of Matrix-supported conglomerate with quartzite clast, near Bayana Town, Bayana Formation

Photo 11. Field photograph showing Large-scale tabular cross-beddings in Umraind village, Damdama Formation

Kanawar village

A 14 m thick lithostratigraphic section (Figure 13) is measured near Kanawar village. The section is composed of sandstones. Various sequences of bed from the top to the bottom are as follows:

12.0-14.0m: Medium-grained, light brown, hard and compact sandstones. Tabular and trough cross-beddings (Photo 12). Wavy bedding is also seen.

10.5-12.5m: Thick-bedded, medium-grained sandstones. Presence of both trough and tabular cross-beddings. Asymmetrical ripples and tabular cross-beddings are seen.

9.0-10.5m: Thick-bedded, medium-grained sandstones. Interference ripple marks, asymmetrical ripples and tabular cross-bedding.

8.0-9.0m: Light brown medium-grained sandstone. Both tabular and trough cross-beddings are present.

6.5-8.0m: Thick-bedded sandstone. Large scale trough cross-bedding, ripple marks. Channel sandstone bodies with fine laminations.

5.5-6.5m: Medium-grained, light brown sandstones.

4.5-5.5m: Yellow brown, medium-grained sandstones, tabular cross-beddings.

4.0-4.5m: Hard and compact sandstones, trough cross-beddings.

3.0-4.0m: Medium-grained, brown, massive sandstone.

2.0-3.0m: Medium to fine-grained, yellowish to brown sandstone. Trough cross-beddings. Laminations are common.

0.0-2.0m: Thick-bedded, yellowish brown, medium to fine-grained sandstones. Asymmetrical ripples.

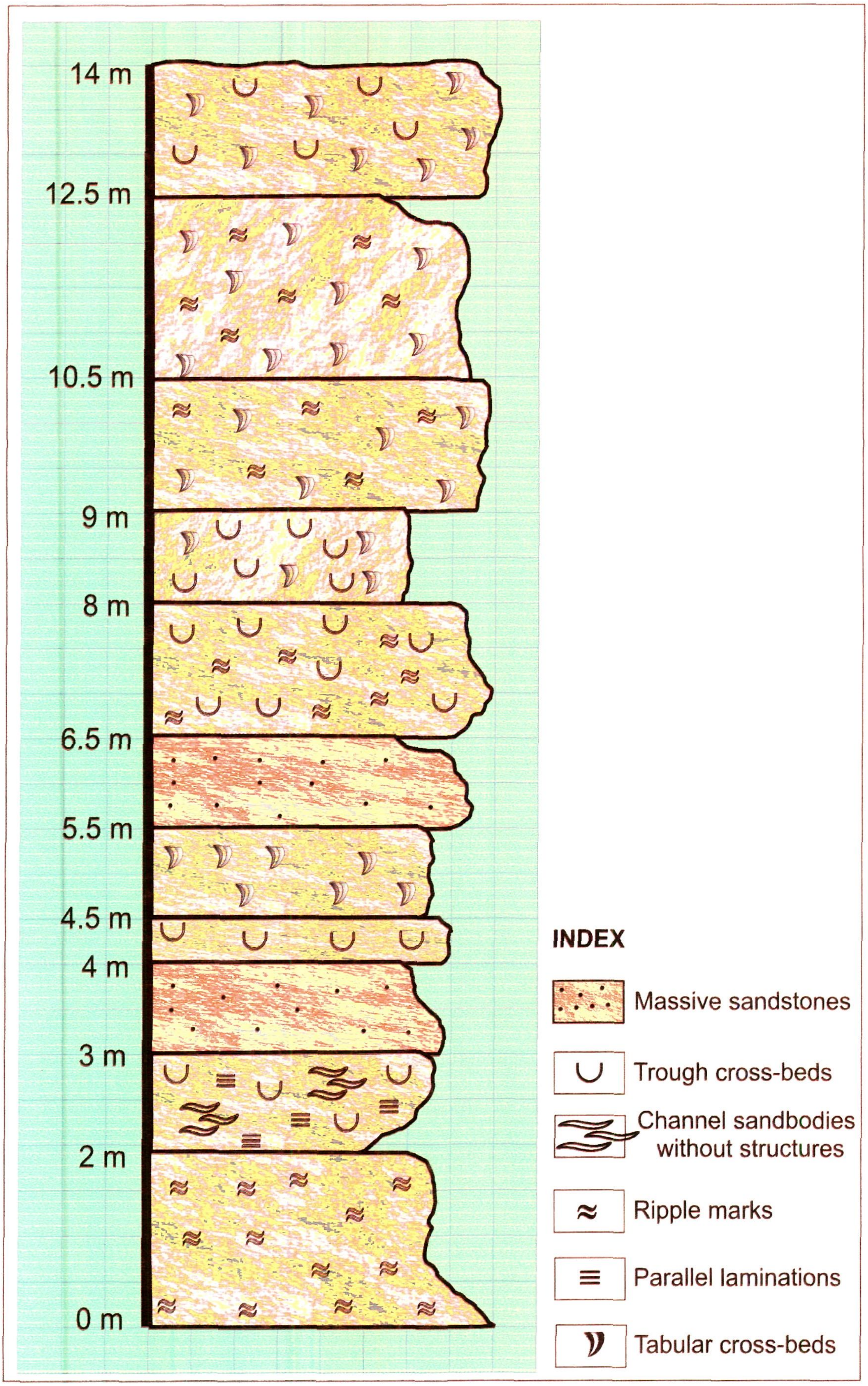


Figure 13. Lithostratigraphic section of Kanawar locality of Damdama Formation

Weir Formation

Weir village

The lithostratigraphic section (Figure 14) measured near Weir village is 18m thick and has following sequences:

15.0-18.0m: Medium-grained, pink sandstone. Ripple marks are abundant.

13.0-15.0m: Medium-grained, light pink, laminated sandstone.

9.0-13.0m: Medium-grained, pink sandstone. Tabular cross-bedding.

8.0-9.0m: Medium-grained, light pink, laminated sandstone.

6.0-8.0m: Medium-grained, light pink, laminated sandstones. Asymmetrical ripple marks are common (photo 13).

1.0-6.0m: Medium-grained, white to light pink sandstones. Trough cross-beddings and ripple marks are common.

0.0-1.0m: Medium-grained, light pink sandstones, wavy beddings.

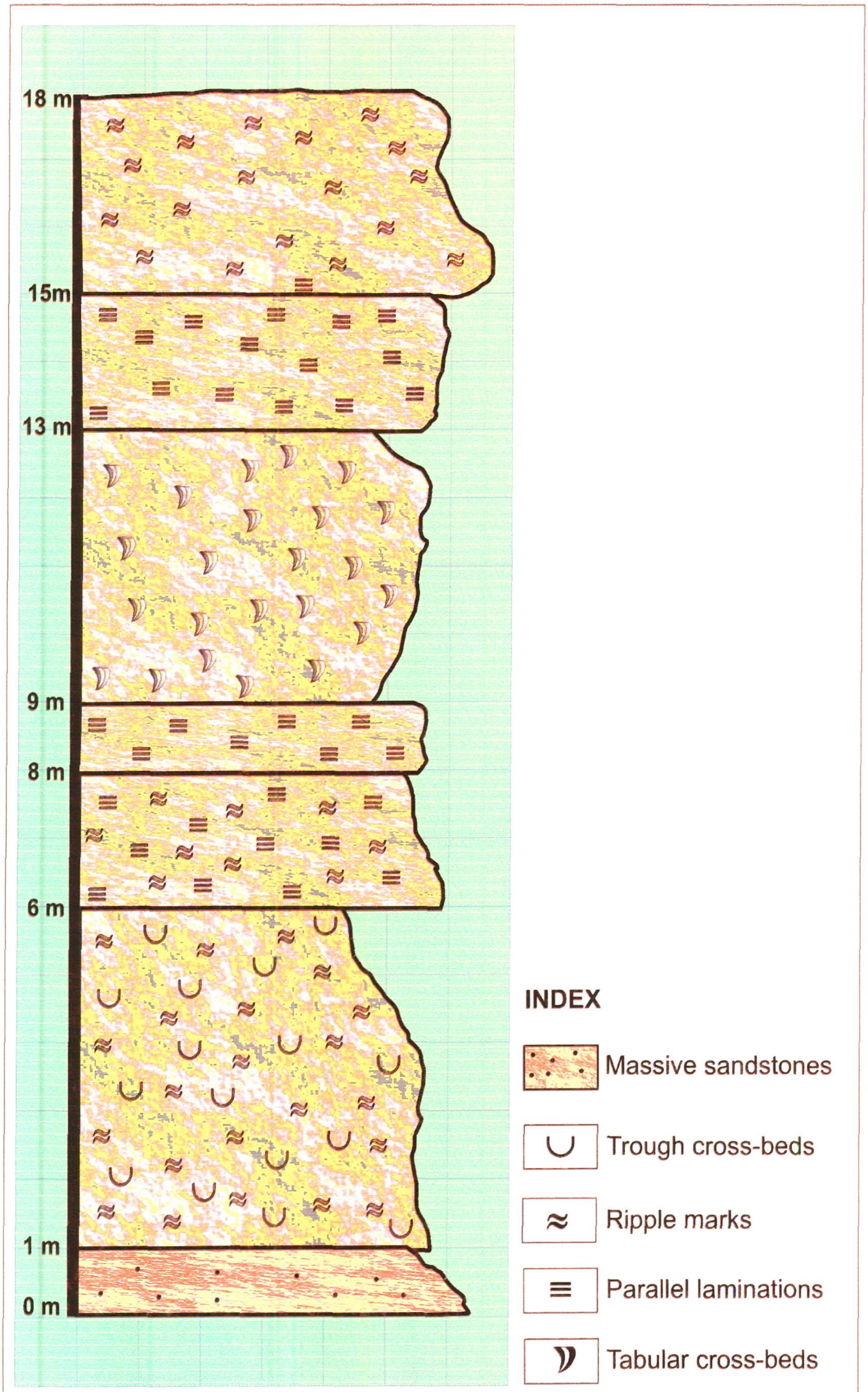


Figure 14. Lithostratigraphic section of Weir Formation

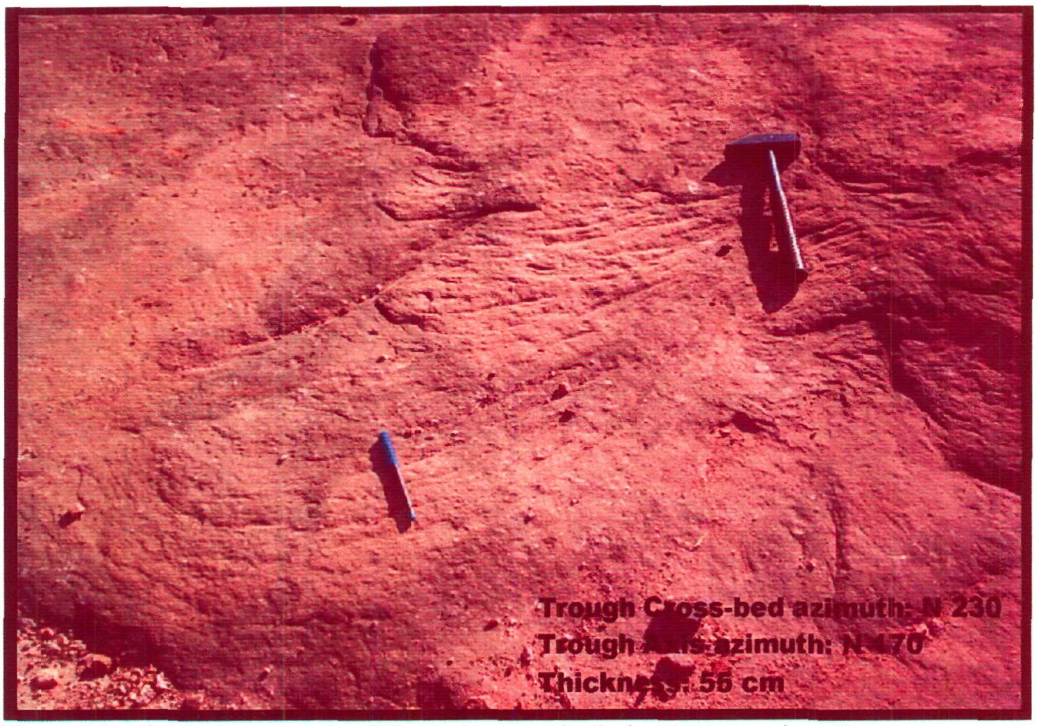


Photo 12. Field photograph of Trough cross-beds in Kanawar locality, Damdama Formation

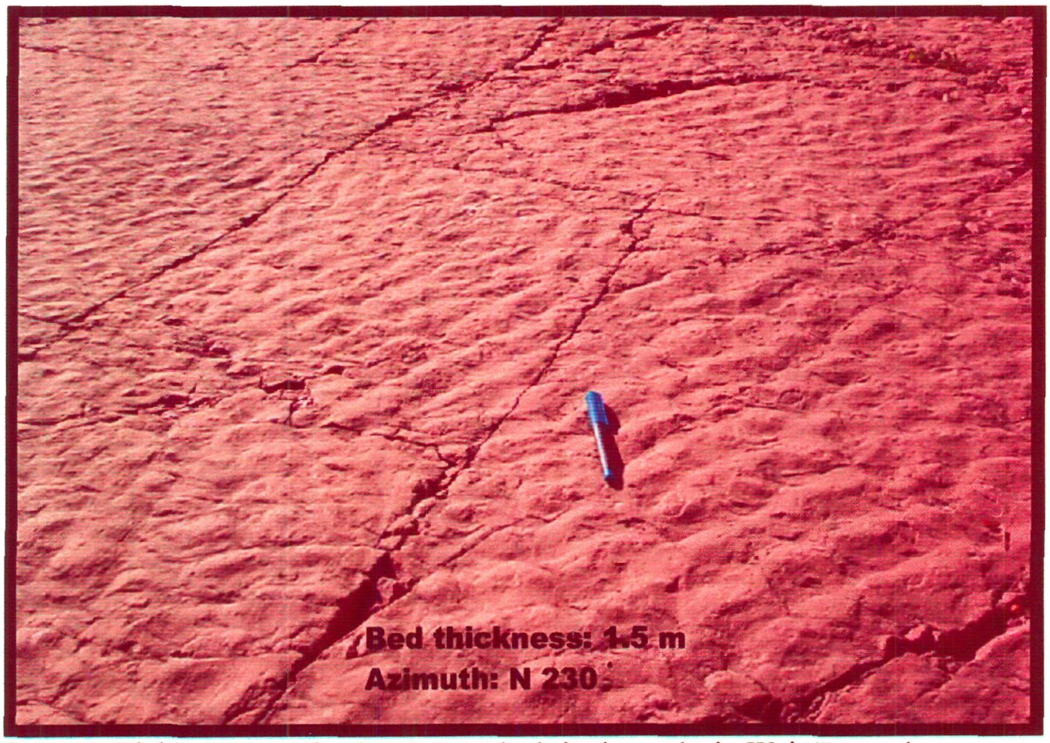


Photo 13. Field photograph of Asymmetrical ripple marks in Weir Formation

Facies Analysis
&
Sedimentation History

CHAPTER - III

FACIES ANALYSIS AND SEDIMENTATION HISTORY

A detailed study of sedimentary facies warrants understanding the depositional environments and basin-fill processes during the initial stage of the basin formation. The present work presents the results of a detailed description of the stratigraphic sections in the study area, to decipher sedimentary processes and depositional environments. On the basis of the information gathered from the area, a depositional model has been suggested.

For this purpose, various signatures in the sedimentary rocks were recorded from several sections. Most of the physical parameters such as bedding and other characters like nature of contact between beds, texture and related small-scale structures, as well as directional properties, such as cross-bedding were studied at different outcrops. In addition, lateral and vertical facies relationship and three-dimensional geometry of depositional units were recorded.

In most studies, the term 'Facies' has been first given a brief descriptive designation and subsequently an environmental interpretation. A facies is a generally body of rocks with specific characteristics, which can be handled at outcrops or from boreholes and thus defined on the basis of color, bedding, composition, texture, fossil content and sedimentary structures (Reading, 1986). In the present study, the term 'Facies' has been employed in an interpretative sense following the reconstruction of ancient depositional processes and their environments in different localities. The interpretation of facies is based on the study of their spatial relationship and internal characteristics (lithology and sedimentary structures etc.) and comparing this information with the knowledge gained from recent sedimentary environments and well studied stratigraphic units. Subdivision of a rock sequence into constituent facies (or units of similar aspect) is essentially a classification procedure and the degree of subdivision is basically governed by the objectives of the study.

The construction of a depositional model for a rock-sequence is one of the basic aims of stratigraphic analysis. A facies model could be defined as 'a general summary of a specific sedimentary environment' (Walker, 1984), constructed by synthesizing many studies of both ancient sedimentary sequence and recent sediments.

A total of fourteen lithofacies have been recognized in the study area. The sedimentary facies are defined on the basis of lithology and sedimentary structures observed in them. The lithofacies identified are as follows:

(a) Clast supported conglomerate facies (Gc): This facies occupies the base of the Nithar Formation (Photo 2) and attains a maximum thickness of 85 m. This thick-bedded, clast-supported conglomerate facies possess lenses of cross-bedded pebbly sandstones. It is composed of clasts of quartzite and vein quartz with maximum clast size of 40 cm. The clasts are disorganized in nature, rounded to sub-rounded and moderately spherical in shape. The matrix is mainly composed of coarse sand and granules of vein quartz.

(b) Matrix-supported conglomerate facies (Gm): The matrix-supported conglomerate is exposed near Sitakund village (Sita Conglomerate), Bayana Town (Mahloni Conglomerate) and Umraind village (Umraind Conglomerate). Near Sitakund, alternate beds of ferruginous conglomerate and sandstone are present forming the lower part of the Jogipura Formation. The phenoclasts are quartzite, vein quartz and occasionally red jasper. Pebbles are arranged in a linear direction. The conglomerate beds show wavy contacts with sandstone beds. Mahloni conglomerate exposed near Bayana Town (Photo 9) is different from other lithosections in having alternation of conglomerate and sandstone beds. It is massive and thickest of the entire conglomerate facies in the area. The maximum clast size is upto 10 cm. The phenoclasts are commonly composed of brown and pink quartzite (Photo 10), sandstone, vein quartz and occasional small jasper. The matrix is coarse-grained sand at the base and finer to medium-grained sand at the upper part of the section. The paraconglomerate exposed near Umraind village is wedge-shaped and poorly sorted. The maximum size of clasts is upto 18 cm and clasts are in the form of vein quartz, quartzite, sandstones, feldspars and occasional jasper.

The conglomerate which represents the upper part of the Damdama Formation with an average clast size of 1-5 cm occurs as thick bands at the base, as lenses and sheets higher up section extending along the strike for a few hundred meters. The conglomerate is poorly-sorted, clast-supported and polymictic. The lower and upper bounding surfaces are erosional.

(c) **Tabular cross-bedded sandstone facies (Sp):** This facies is characterized by medium to coarse-grained, poorly sorted, earthy yellow sandstones. The sandstone beds show decrease in grain size upward. The facies is observed in Bhimnagar, Umraind (Photo 11), Kanawar, Bhagrain (Photo 6) and Alapuri sections. The individual cross-bedded units vary in thickness from 0.40 m to 2 m. Cross-beds occur both in co-sets and in single sets. Parallel lamination is also observed. Small-scale, low-angle tabular cross-bedded sandstones are also observed in Weir, Sitakund and Nithar formations. Here the cross-bedding sets are 0.05 to 1 m thick and occur also in co-sets. The bounding surfaces of cross-beds are undulating.

(d) **Trough cross-bedded sandstone facies (St):** Trough cross-bedded sandstones are present on large scale in Bhimnagar, Umraind, Kanawar (Photo 12), Bhagrain and Alapuri sections and on small scale in Bayana, Weir, Sitakund and Nithar formations. The sandstone is medium to coarse-grained, pale yellow to brown colored. Trough cross-bedded units are occasionally distorted (Photo 8, Figure 10), swaley-type in places. The width of the trough ranges from 1.5 to 8.0 m and amplitude ranges from 0.3 to 2.5 m.

(e) **Parallel laminated sandstone facies (Sl):** This facies is common in Bayana, Bhimnagar, Nithar, Weir, Sitakund and Alapuri (Photo 7) as well as Bhagrain sections. The sandstone is medium-grained, light yellow to brown colored, moderately sorted. Individual beds range in thickness from 1 to 5 m. Beds are tabular and some have rippled top. The beds are mostly evenly laminated. Some beds have combination of horizontal lamination and low-angle cross-beds. The bed contacts are sharp.

(f) **Pebbly sandstone facies (Sp_l):** This facies occurs in Bayana, Sitakund and Umraind localities. The coarse-grained sandstone varies in grain size from coarse sand to pebble and 10-30 percent of the rock is constituted by clasts. Maximum size of pebble is 6 cm. Some of the beds pass upward to plane laminated pebble-free sandstones. Base of the beds is erosive.

(g) **Ripple bedded sandstone facies (Sr):** This facies consists of light yellow to brown and gray medium-grained sandstone. Ripple bedded sandstones are common in Jahaj-Govindpura volcanic section, Sitakund, Kanawar as well as Weir sections. The sandstone is moderately to well-sorted and thinly bedded. Both symmetrical and asymmetrical ripples (Photo 13) are common. Occasional occurrence of interference ripples is observed in Damdama and Jogipura (Photo 4) formations. Crest of the ripples are straight to sinuous, sometimes rounded and flat.

(h) **Tuffacious sandstone facies (Ts):** This facies outcrops at the Hathori locality of Jahaj-Govindpura volcanic Formation. It occurs as 5-50 m thick sandstone interbeds in the Jahaj–Govindpura volcanics. At the lower part of the section, the tuffacious sandstone is dark gray in color, medium to fine-grained, while at the middle and upper part, it is pebbly and poorly stratified. Thick and massive bedded tuff and medium to fine-grained thin bedded tuffs constitute the major pyroclastic deposits (e.g., Singh, 1985). Ripple lamination, parallel lamination and torrential bedding are observed. Tabular cross-beds and symmetrical ripple marks are found in upper part of the section. Spatter, agglomerate are associated with tuff (Photo 3).

(i) **Interbedded shale and thinly bedded fine-grained sandstone facies:** The finer clastic assemblage of interbedded sandstone and shale occurs in the Nithar Formation. The sandstones are thick-and-thin bedded, light yellow in color. The sandstone beds are thin and wavy, fine-grained and exhibit solitary sets of parallel lamination, small-scale cross-beds and ripple marks. Herring-bone cross-beds occur in upper part of the section. The shale is red in color and faintly laminated. The facies shows gradational contacts with other facies units.

(j) **Interbedded conglomerate and sandstone facies:** This facies occur at the Bayana, Sitakund and Umraind localities. It comprises alternate sequence of polymictic conglomerate and sandstones. The conglomerate occurs as thick bands at the base and as sheets and lenses at the upper part of the localities and it is matrix-supported. Average size of the clast of conglomerate is 1-3 cm. Thick-and-thin nature is observed. The conglomerate is poorly sorted. The sandstones are medium to fine-grained, hard and compact and show lateral extent upto 100m. Tabular and trough cross-bedding is seen in the sandstones. The whole section shows upward decrease in grain size.

(k) Hummocky cross-bedded sandstone facies (S-hcs): This facies is observed in the middle part of the Umraind section. It consists of 2.5 m thick bed of sandstone, which is light brown, medium-grained and pebbly. The upper part of the section shows hummocky cross-bedding. The hummocky cross-beds are however, poorly developed and may be delineated and stretched only on close examination. They are either aggradational or originated from laminae drapping shallow and very low angle truncations. Laminae are parallel and conform to the underlying surfaces and show downlap and onlapping relationship with underlying surface at very low angle. The hummocks are commonly built up sets of tabular laminae without erosion (e.g., Brenchley and Newall, 1982 ; "Active hummocks" of Boss et.al., 1988).

(l) Herring-bone cross-bedded sandstone facies (S-hb): The facies is observed in the lower part of Bayana and upper part of Nithar Formation. In Bayana section, herring-bone cross-bedding is seen in a channel sandstone body within a bed of basal conglomerate, 3.5 m thick. In Nithar locality, herring-bone cross-beds have developed in a 4 m thick sandstone bed (Photo 1). The sandstone is gritty to medium-grained, thick-and-thin-bedded, and occasionally laminated. Herring-bone cross-beds are associated with tabular cross-bedding and ripple marks.

(m) Channel sandstone facies (Sc): This facies is developed in the Bayana and Damdama formations. The facies comprises of medium to fine-grained sandstones. In Bayana locality, channel sandstone bodies are characterized by presence of tabular cross-bedding, herring-bone cross-bedding, mud cracks and laminations. Channel sanbodies are lenticular in shape and bed contacts are wavy.

PALAEOCURRENT INTERPRETATION

Palaeocurrent study gives vital information on palaeogeography, sand body geometry and sediment provenance (Potter and Pettijohn, 1977). Moreover, palaeocurrent patterns also provide a clue to the depositional environments (Klein, 1967; Selley, 1967), as every major environment has a particular current system which has a specific relationship to regional slope and depositional strike. The currents normally follow the slope in a fluvial environment whereas in case of coastal environment, the currents are highly variable in direction. Palaeocurrent data helps in deciphering depositional environment, shoreline orientation, palaeoslope, onshore, offshore and longshore currents. Palaecurrent analysis also helps in determining pattern of sediment dispersal.

Singh (1991) opined that the Bayana sub-basin has a WNW-ESE trend of shoreline, NNE palaeoslope along the basin length, north-westerly and south-easterly palaeoslope across it, and a multi-directional sediment dispersal pattern in offshore, onshore and longshore direction.

This study is not extended to the determination of palaeoslope and shoreline orientation, but limited to the recognition of various palaeocurrent directions and pattern of dispersal of clastic sediments in onshore, offshore and longshore pattern. This is because of lack of relevant data from individual formations. Azimuths of tabular cross-beds and trough cross-beds yielded insufficient data from the individual formations; because of which they are analyzed on a composite basis. Another reason for composite analysis of tabular and trough cross-bed is that only one of them is found to be dominant in a particular locality/formation. Ripple marks were observed occasionally in the study area and their palaeogeographic interpretation was not attempted in view of the paucity of data. Lack of directional structures restricts systematic collection of data from some of the formations. Therefore in this study, azimuths of tabular and trough cross-bed data are used on a composite basis to reconstruct the orientation of palaeocurrent and then the current directions are related to the shoreline and palaeoslope determined by Singh (1991), to infer the sediment dispersal pattern.

Cross-beddings were studied with respect to:

(1) Scale (thickness of sets of cross-bedding)

(2) Inclination (dip angle of foresets with respect to the true bedding).

(3) Azimuths of dip of the foresets and their variability.

A total of 235 measurements of azimuth of cross-bedding (both trough and tabular) were collected from 10 localities belonging to 7 formations. Among them are 30 azimuthal data collected from Nithar village locality of Nithar Formation, 35 from Jahaj-Govindpura volcanic locality, 30 from Sitakund village of Jogipura Formation, 25 from Bhagrain and Alapuri localities of Badalgarh Formation, 45 from Bayana town and Bhimnagar localities of Bayana Formation, 40 from Umraind and Kanawar localities of Damdama Formation and rest 30 from Weir locality of Weir Formation .The inclination of cross-bedding was measured on foreset planes of tabular and trough cross-bedding. Their inclination value varies from 6^0 to 46^0.

Methods and presentation of data: The cross-bed data sets are first subjected to tilt correction with the help of stereographic projection (Potter and Pettijohn, 1963). The foreset dip azimuths obtained are divided into 30^0 intervals and rose diagrams are prepared. The variability analysis of cross-bedding azimuths involved following steps:

1. Study of the pattern of rose diagrams.
2. Calculation of vector mean (θV) and vector magnitude (L%) by vector summation method of Curray (1956).

As the number of azimuths of any particular formation rarely exceeded 40, their standard deviation and variance are not calculated. Similarly "modal vector mean" are not calculated as most of the rose diagram patterns are bimodal to trimodal. Most of the palaeocurrent patterns are trimodal, followed by bimodal & quadrimodal (Figure 15). The vector mean (θV) for various formation is in the ranges of 55 to 354 and vector strength (L%) values in the range of 20 to 49 (Table 3). The bimodal to quadrimodal distributions with modes oriented approximately at 90^0 reflect the possibility that sediments were transported along the slope, (e.g., Akhtar ,1978 ; Singh, 1991). Therefore to reconstruct the sediment dispersal pattern,

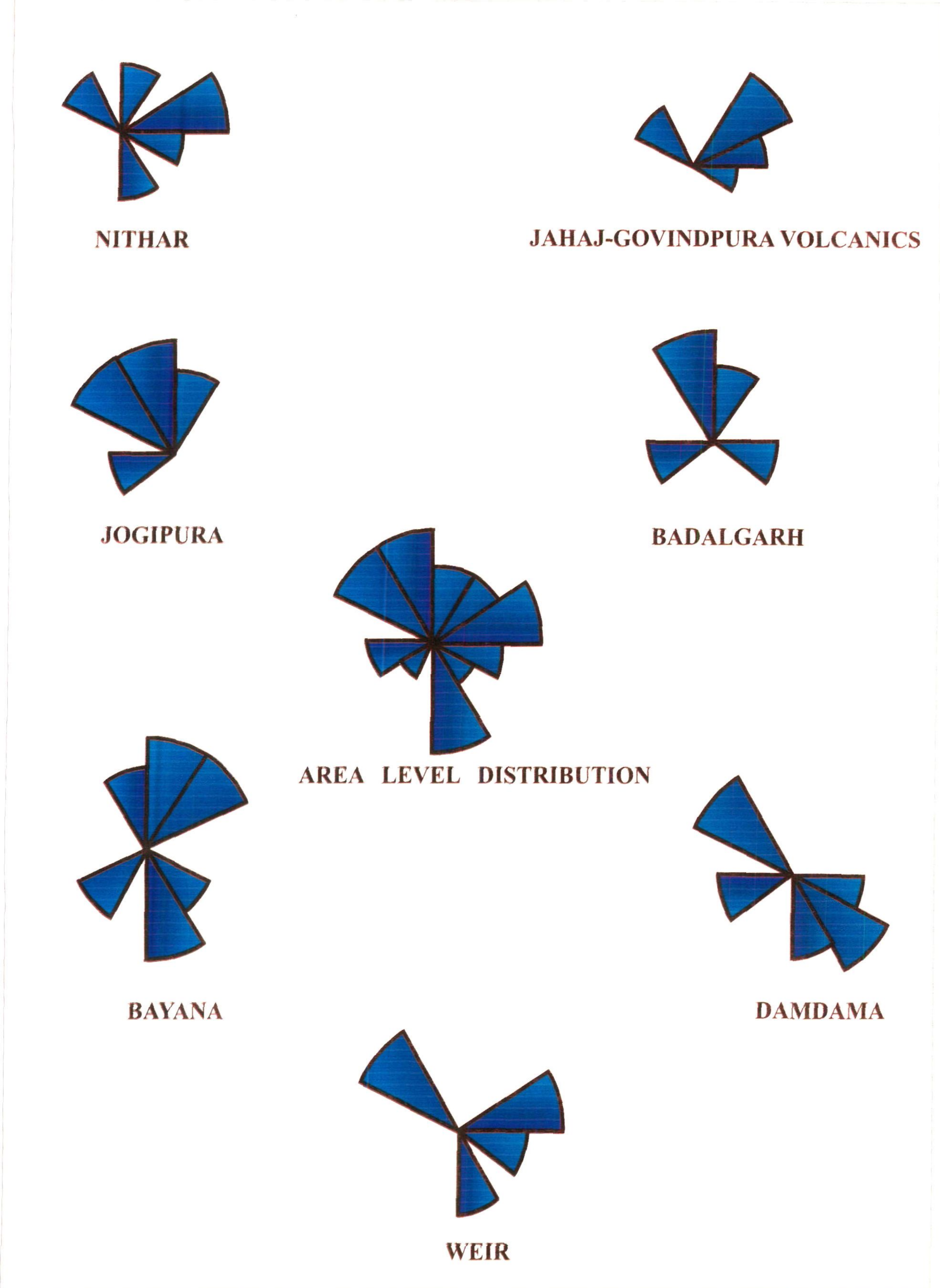


Figure 15. Palaeocurrent distribution patterns in different formations of Bayana Basin

the 360^0 circle was divided into different quadrants, representing offshore, onshore and along the shore current (e.g., Akhtar, 1978). The circle was divided into four quadrants with reference to the 104^0-284^0 trend of shoreline as determined by Singh (1991), (Figure 16). The current azimuths which fall in the quadrants 2 and 4 are considered to represent longshore sediment transport and those in quadrants 1 and 3 represent offshore and onshore current transport respectively (e.g., Akhtar, 1978 ; Singh, 1991).

Sediment dispersal pattern

The bimodal to quadrimodal distribution of cross-bedding azimuths of different localities belonging to various formations indicate dispersal of sediments by multidirectional currents in nearshore shallow marine environments (e.g., Klein,

Table 3. Nature and statistical parameters of Palaeocurrent data.

Formations	No. of distribution	Nature of distribution	Statistical parameters	
			Vector mean (θV)	Vector magnitude (L %)
Nithar	30	Quadrimodal	70	36
JGV	35	Bimodal	55	49
Jogipura	30	Bimodal	327	31
Badalgarh	25	Trimodal	354	42
Bayana	45	Trimodal	66	23
Damdama	40	Trimodal	71	43
Weir	30	Trimodal	86	20

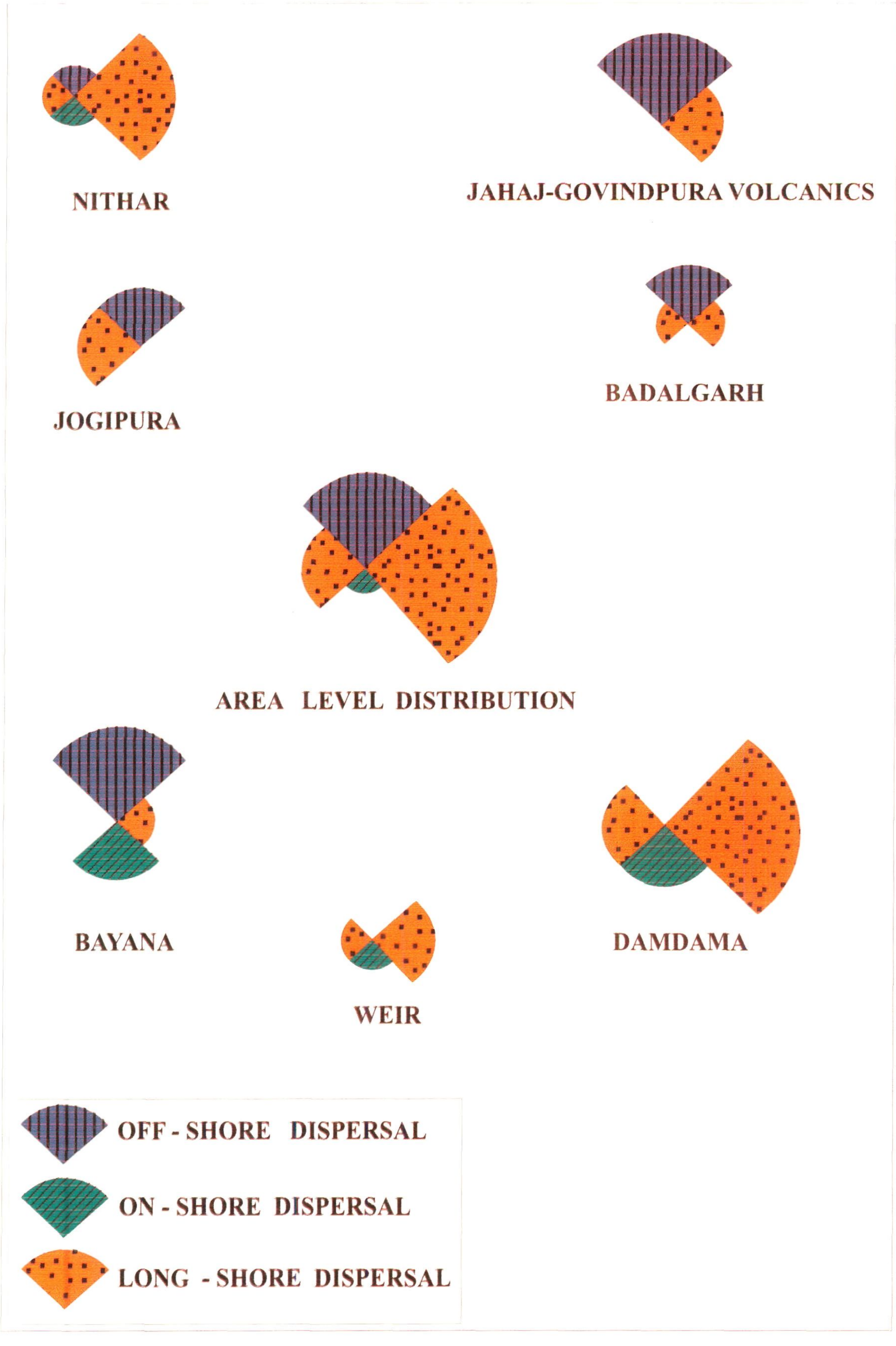


Figure 16. Pattern of sediment dispersal in various formation s of Bayana Basin

1967; Selley, 1967). In the Nithar Formation, quadrimodal distribution of palaeocurrent suggests the involvement of several current systems in sediment dispersal. However east-south-east longshore currents played the major role in sediment dispersal. Some sediments were also carried by west-north-west longshore current, offshore as well as onshore currents. The south-east sediment transport is same to the herring-bone cross-bed direction noted in the Nithar Formation. Thus the sediments were dispersed dominantly by across-slope current. In Jahaj-Govindpura volcanic Formation, bimodal distribution of palaeocurrent pattern indicates two main sediment transport directions. The Northward offshore current was dominant dispersing agent while east-south-east longshore current too was equally active.

The sediment dispersal pattern of Jogipura Formation comprises of two current systems, which is evident by bimodal distribution of rose diagram. Northward offshore dispersal as well as west-north-west longshore dispersal and both were significant. Preferred orientation of pebble elongation direction noted in this formation suggests west-north-west longshore current.

The rose diagram of the Badalgarh Formation indicates three current directions oriented at 90^0, offshore dispersal was dominant while west-north-west and east-south- east longshore dispersal was less prominent. The trimodal distribution of palaeocurrent pattern in Bayana Formation clearly shows significance of offshore and onshore currents in sediments dispersal. A small part of sediment was also dispersed by east-south-east longshore current. The dominance of two main sediment transport directions suggests reversal of current direction. Sediment dispersal by reversing current is characteristic of tidal environment and the two directions in all probability represent flood and ebb currents. This is further evident by the presence of herring bone cross-beds of azimuth $N42^0E$ in the lower part of this formation. The channel sandstone body present in lower part of the formation with axis oriented at $N10^0W$ direction is related to strong offshore dispersal. Another sandstone body which occurs at the middle part of the formation has axis $S40^0W$ suggesting prominent onshore dispersal. Thus combining all the above evidences, conclusion can be drawn that sediments were dispersed both landward and basinward by strong flood and ebb currents.

Three current systems are indicated by trimodal rose diagram pattern of Damdama Formation. East-south-east longshore dispersal was dominant followed by west-south-west longshore and onshore dispersal .Azimuths of hummocky cross-beds indicates strong south-east longshore dispersal. However channel sand body with S15^{0}W oriented axis in lower part of Umraind locality of this formation suggests that onshore dispersal was also prominent. Trimodal rose diagram of Weir Formation indicates involvement of east-south-east longshore current, west-north-west longshore current and onshore current, among which east-south-east longshore current was the dominant dispersing agent.

The composite distribution of cross-bedding azimuths aggregated from the study area indicates dispersal of sediments from four different directions, indicating multidirectional clastic transport in offshore, onshore and longshore direction.

FACIES ASSEMBLAGES

Individual facies may not be diagnostic of any particular environment. Facies assemblages signify collection of multiple facies resulting from genetically related accumulation and modification. It constitutes several lithofacies that occur in combination, and typically represent one depositional environment. Lithofacies interpretation forms the primary tool for identifying the depositional conditions under which the sediments were deposited and preserved. In this study, four distinct facies assemblages have been identified based on association of lithofacies with one another, their textural characteristics and sedimentary structures and their environment of deposition is interpreted.

Facies Assemblage A: Tidally influenced Fluvial Deposits

The lithofacies which represent the facies Assemblage A are: Tabular/trough cross-bedded sandstones, herring-bone cross-bedded sandstones, interbedded sequence of clast-supported polymictic conglomerate and sandstone, matrix-supported conglomerate interbedded with medium to fine-grained, cross-bedded sandstones. Clast-supported conglomerate are coarse-grained and have subangular to subrounded clasts of quartzite and vein quartz. Matrix-supported conglomerate occurs as thick bands at the base and as sheets and lenses at the upper part of the measured section. Average size of the clast of conglomerate is 1-3 cm. The conglomerate is poorly sorted, unstratified, shows thick-and-thin behavior. Clasts have no particular directional orientation. The facies assemblage is dominated by medium to fine-grained, hard and compact, tabular and trough cross-bedded sandstones, with erosional basal surface which are laterally extended showing fining upward sequence.

Interpretation

Clast -supported conglomerate facies with thick sequence of conglomerate beds can be interpreted as bed-load deposition (e.g., Reading, 1986; Rust and Jones, 1987; Amireh et al.,1999; Jo and Chough, 2001). Poor-sorting and disorganized nature of clasts further indicates highly fluctuating velocity of transporting medium as well as its rapid deposition from high-concentration sediment dispersions (e.g., Uba et al. 2005) by tractive current. The matrix-supported beds of conglomerate which display features like disorganized framework of clasts, poor-sorting, lack of stratification, presence of clasts in the top of the bed etc. has been interpreted as debris-flow deposits (e.g., Massari et.al., 1993; Khalifa et. al. 2006). Trough cross-beds are product of mega ripple migration in the active channels during prolonged high-water stage. The tabular cross-beds are formed by lateral accretion of transverse bars. Presence of herring-bone cross-bedding in sandstones clearly indicates tidal influence. More or less unidirectional (SE & NW) cross-beds in sandstones, together with basal erosion surfaces, and lack of wave influence suggest deposition in fluvial channels.

Facies Assemblage A is attributed to tidally-influenced fluvial channels formed in proximal estuarine areas, near the limits of the fluvial realm. Although weak, tidal currents might reach these inner estuarine areas and rework sediments brought from the fluvial channels. The poor sorting, coarse to medium sand size, absence of bioturbation etc. are features that lead to suggest a fluvial origin for this facies assemblage, distinguishing it from other channel deposits formed under dominantly tidal processes. Presence of cross-beds in sandstones with foresets dipping at low angles indicates evidence of tidal influence, as migration of 2D- and

3D-bedforms in tidal settings typically results in cross beds that display low angle dipping foresets (e.g., Shanley et al., 1992; Plink-Bjorklund, 2005). Erosive bases and fining/thinning upward trends indicate deposition within channels. Possible interpretation is that a fluvial system is flooded during a transgression to form estuarine-setting.

The fining-upward facies sequences are the best recognizable characteristic of the fluvial deposits. Identification of these fining-upward sequences in general is that they consist of massive or thick-bedded conglomerates, or very coarse- to medium-grained, planar cross-bedded sandstone. The facies assemblage generally develops into coarse- to medium-coarse and fine -grained, cross-bedded and cross-laminated sandstone.

Tidal estuary is the place where interplay of fluvial as well as tidal processes can be seen. Dalrymple et al. (1992) defined an estuary as 'the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes (Figure 3). The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth'. It is further proposed that most estuaries comprise three zones: (1) an *outer zone* dominated by marine processes, (2) a *central zone* where marine energy is dissipated by fluvial currents, and (3) an *inner, river-dominated zone*. Relating this to the present work, it can be interpreted that fluvially derived sediments were modified by shallow-marine processes in the central zone of an estuary where marine energy is dissipated by fluvial currents.

Facies Assemblage B: Tidal flat / Inter Tidal deposits

Facies assemblage B consists of a tabular package, essentially dominated by different types of sandstone facies like tabular cross-bedded sandstones, herring-bone cross-bedded sandstone, trough cross-bedded sandstone, ripple-bedded sandstone, parallel laminated sandstone along with interbedded shale-thinly bedded fine-grained sandstone facies. The sandstones are medium-grained, moderately sorted. Tabular cross-sets are present mostly in large-scale but small scale tabular as well as trough cross-sets are also there. Herring-bone cross-sets are present in medium-grained, hard and compact, moderately sorted sandstones. Parallel lamination is seen in thinly bedded medium to fine-grained sandstones. Shale is subtly laminated; sandstones are fine-grained to gritty with wavy contacts.

This assemblage is internally characterized by an overall fining- and thinning-upward succession

Interpretation

Tabular geometry of the facies assemblage B suggests deposition in a flat-lying area. Large-scale tabular cross-bedded sandstones can be interpreted to be a deposit of inter-tidal flood ramps, lateral accretion of tidal channel bars (e.g., Casshyap and Aslam, 1992 ; Allen & Leather,, 2006). Presence of small-scale cross-bedding in assemblage with lamination, ripple marks etc. suggest mixed tidal flat depositional environment. (e.g., Reineck and Singh, 1975). Moderately sorted sandstones and paucity of silt and clay indicate sediments were subjected to prolonged reworking by wave and tidal currents. Ripple bedded sandstone facies represents shallow water sand flats in tidal depositional settings Flat and rounded tops of the ripple bedform reflect planning-off during tidal reversal (Klein, 1970a). Undulation in ripple-crests implies a transition from low energy to high energy conditions. The wave- or current generated ripple beds are common in sandy tidal flats or relatively shallow tidal channel margin (Meyer et al., 1998).

When the tidal currents are too slow to produce ripples, they produce sand layers from suspension (Dalrymple, 1992), as seen in parallel laminated sandstones. The parallel laminated sandstones facies can be formed during occasional periods of storm in intervening periods of low sediment influx and in intermittent inter-tidal environment. Cross-beds associated with laminated beds suggest their deposition on beach-face environment under the influence of strong tidal and longshore currents. Their environment of deposition can be interpreted to be inter-tidal (e.g., Khalifa et al., 2006). The presence of herring-bone cross-beds reflects the bed load deposition by reversing tidal currents of equal bed shear intensity and bottom current velocities. Flow direction reversals are associated with both rising flood and falling ebb stage of tidal cycle and these reversals are generally bi-polar in orientation. Reading (1978) and Reineck & Singh (1980) attributed these sedimentary structures to tidal environment of nearshore (barrier associated) deposits. Collinsion & Thompson (1984) and Moore (1979) attributed this facies to have formed in inter-tidal and shallow sub-tidal environment. Reading (1978) attributed herring-bone type cross-bed in sandstone as diagnostic feature of tidal currents. Collinsion & Thompson (1984) attributed these structures to inter-tidal and shallow sub-tidal environment. Lesser occurrence of herring-bone cross-beds presumably record relatively weak tide (e.g., Chakraborty et al'1999). Occurrence of characteristic sedimentary structures like parallel lamination and ripples associated with herring-bone cross-beds are interpreted to have deposited in upper sub-tidal to lower inter-tidal sub-environment.

The facies interbeds of fine-grained sandstones and red shale indicate its deposition in a lower shoreface transition zone of inter-tidal mixed flat environment. Almost equal representation of sandstone and shale, abundance of small scale wave and current formed sedimentary structures suggest their deposition in rather low energy intertidal mixed flat environment (e.g., Evans, 1965; Van Stratten, 1954 ; Corcoran et.al., 1998). Here, the intertidal environment is characterized by alternating levels of high energy (cross-bedded sandstones) and low energy (shale) condition. The interbedding of shale reflects a transition from a wave-agitated shoreface-foreshore setting to below wave base depositional setting. Red shale is a quiet deep-water deposit, formed by settling of particles from suspension. Presence of lamination and absence of wave-generated structures in the shale suggest deposition in a quiet water environment below wave base (e.g., Mukhopadhyay and Chaudhuri 2003).

Fining upward sequence of the facies assemblage suggests a decrease in flow velocity and sand supply linked to tidal flat shallowing. Tidal flats that developed under progradational conditions are characterized by a fining-upward succession, consisting of coarse sediments at the base and progressively finer sediments toward the top in an uninterrupted vertical sequence. This common relationship reflects decreasing energy in a progression from subtidal to intertidal parts of the tidal flats. Tidal flat deposits commonly overlie estuarine channels in the inner to middle zone of valley systems (Allen, 1991), but also occur along the site of whole estuary (Dalrymple et.al.,1992).

Tidal flats occur on open coasts of low relief and relatively low energy. The conditions necessary for development of tidal flats include an effective tidal range and the absence of strong wave-induced currents. The intertidal zone is a part of the tidal flat, lying between high and low tide range which makes up the major areal extent of the tidal flat. If a noticeable variation in sediment type is present throughout the flat, for example sands and shale, the intertidal area commonly possesses alternating layers of both textures. Intertidal and subtidal parts of tidal flats are continuously affected by tidal currents as well as wind-induced wave currents. Current velocity can be highly variable in different settings in the same area under different conditions. Therefore, intertidal environmental settings are very sensitive coastal areas where wave action is moderate and river input is small. They are the manifestation of progradation of sediments derived from a marine sediment source and can occur in lateral accreting tidal-dominated estuaries or wave-dominated inner parts of estuaries.

Facies Assemblage C: Tidal channel deposits

Facies Assemblage C is characterized by the presence of four lithofacies; large scale trough cross-bedded sandstones, large scale tabular cross-bedded sandstones, parallel-laminated sandstones and channel sandbodies. Sandstones are medium to coarse-grained and moderately sorted. Sandstones are mainly thin-bedded, which change to thin-and-thick pattern in some places. Cross-sets are generally low angled. Sandstone beds internally show upward-fining nature. Palaeocurrent direction of the tabular cross-beds show bi-directional pattern. Reactivation surfaces are present within cross-sets of sandstones.

Interpretation

Large-scale trough cross-bedded sandstones can be interpreted to be the result of lateral migration of sand dunes of tidal channel bars. Large-scale tabular cross-bedded sandstones are product of migration of large dunes in subtidal channel. Both trough and tabular cross-bedded sandstones are thought to be deposited in tidal/subtidal channels in a nearshore coastal environment. Reactivation surfaces are formed as the subordinate current erodes the lee-face of the dune formed by the preceding dominating current (Dalrymple, 1992).

Thin bedded nature of sandstone indicate tidally influenced environment. Thick-and-thin behavior of the beds further explains influence of ebb and flood tidal current. The upward fining large-scale cross-bedding sets can be interpreted to represent bars in the tidal channel, since the upward fining reflects upward decrease in channel energy (e.g., Sultan and Bjorklund, 2006). The internal organization, configuring thinning- and fining-upward successions attests to deposition during waning flow, typical of channels, prone to lateral accretion.

The channel sandstones can be interpreted as deposit of shallow channels which were characterized by episodic fluctuation in flow velocity and were tidally influenced (Ahmad, 1988). Axis of the channel is parallel to the main palaeocurrent direction. Assemblage of the channel sandstone facies with other lithofacies of tidal origin further suggest that channel sandstones are tidal channel (inlet) deposit (e.g, Shukla and Pant, 1996). Tidal inlets are more or less permanent passages between barrier islands that allow tidal exchange between the open sea and lagoons, bays, and tidal marshes behind the islands. Inlet channels are generally deepest between the tips of the islands and shallow into tidal deltas both lagoonward (flood delta) and seaward (ebb delta). In a typical channel deposit, sands are coarsest in the deeper part of the channel and characterized by mainly ebb-oriented, tabular, planar cross strata, with reactivation surfaces formed by flood-oriented tidal currents. Sands of the channel margin have trough-shaped sets of cross strata formed by both flood-oriented and ebb-oriented dunes, as well as large foresets formed by the lateral migration of the spit.

Internal features that favor channel deposition under the influence of tidal currents include presence of reactivation surfaces within cross sets; oppositely dipping foresets giving rise to bidirectional palaeocurrent data; low-angle dipping cross sets; and thick-and-thin behavior of the sandstone beds. Generation of all these structures requires fluctuating current energy, as occurs most typically in tidal settings. The typical fining/thinning upward successions suggest that tidal channels filled up more or less continuously during rising sea level (Dalrymple et al., 1992).

In nearshore areas (and in offshore areas too, if there's any large-scale relief) tidal currents tend to be channelized into largely bidirectional currents rather than rotary, as tidal dynamics would predict, and such bidirectional tidal currents almost always show some degree of asymmetry, in that the flow in one direction is stronger than the flow in the other direction during the tidal cycle. Tidal channel deposits between the ebb and flood-tidal delta can cover relatively large areas, because the channels and the tidal inlets between the barrier islands frequently migrate parallel to the shoreline. Channel fills usually began at the erosional base with relatively coarse lag deposits. These are overlain by large scale bi-directional tabular and trough cross-beds. On the top of this sequence bidirecttional small to medium scale tabular and trough cross-beds, parallel and ripple laminations are observed.

Facies assemblage C is interpreted as having been formed in tidal inlets (ebb channels) in the lower estuary, and subsequently influenced by a marine environment at its upper part.

Facies Assemblage D: Wave & storm dominated shoreface deposits

Facies assemblage D is made up of symmetrical and asymmetrical ripple bedded sandstones, interference ripple-bedded sandstones, tabular and trough cross-bedded sandstones in large as well as small scale, swaley-type trough cross-bedded sandstones, hummocky cross-bedded sandstone, laminated sandstone and pebbly sandstone facies.

Interpretation

Ripple bedded finer sandstones show features indicating deposition under oscillatory currents of weaker strength (e.g., Chakraborty et al',1999). Reineck and Singh (1980) reported symmetrical wave ripples from 4 m deep water of offshore region and asymmetrical wave ripples from 0 to 2 m deep water of backshore-shoreface zone of Gulf of Gaeta, Italy. Asymmetrical ripples can either be the manifestation of moderately deep offshore water or of much shallower water within the range of backshore-shoreface environment. Abundant asymmetrical ripples with crests oriented parallel to current direction are also a upper shoreface feature (Reading, 1978). Symmetrical ripple marks with rounded crest reflects planning-off during tidal reversal. The facies suggests deposition in wave-dominated shoreface environment (Allen & Leather, 2006). Occurrence of interference ripple marks is significant. They indicate a depositional setting of extremely shallow water regime of backshore-shoreface environment. Interference ripples indicate temporary emergence and a shallow depth of water over the bars (Mukhopadhyay & Chaudhuri, 2003).

Large-scale tabular cross-bedded sandstones indicate high energy combined-flow condition in a storm-influenced lower shoreface environment (e.g., Duke et al', 1991). Small-scale tabular cross-beddings represent deposition in tidal sandsheet bars in upper shoreface. High angle trough cross-bedded sandstones oriented in current direction flowing parallel to shore are product of upper shoreface deposited by longshore current. Abundance of low angle trough cross-beds is indicative of storm-dominated deposition above fair-weather wave base in the mid-to-upper shoreface (e.g., Lackie and Walker,1982 ; Plint, 1988 ; Chakraborty et al', 1999). Swaley-type cross-beddings are deposited under storm waves on shoreface.

Occurrence of hummocky cross-bedded sandstone is a diagnostic feature of stormy condition. The hummocky cross-bedded sandstone is interpreted as a shelf-storm deposit formed in a zone affected by storm waves and wind induced currents (Harms et.al., 1975). Collision and Thompson (1984) found this hummocky cross-bedded sandstone structure in shallow marine shelf sediments and interpreted to have formed by action of storm waves below depth of normal, fair-weather wave reworking. Einsele (1992) described it as a feature of storm-induced lower-shoreface deposit worked upon by combined flow regime of storm-wave induced oscillatory stress. This structure is usually well developed in a zone of significant combined flow, i.e., above the storm wave base, where high energy flow conditions with a strong oscillatory component (orbital velocities >0.5mtr/sec) develop (Einsele, 1992).

The parallel laminated sandstone represent offshore transport of sand during storms on the shoreface (Cheel, 1991; Brenchly et.al.,1993; Allen & Leather, 2006). Depositional condition for the facies comprised wave and storm-related processes operating on a shallow marine shelf. Sands and silt were emplaced and deposited under oscillatory current related to storm and their late-stage phases. Evenly laminated sandstones are produced by heavy storms, which erode sand from upper part of the beach and transfer them into suspension in turbulent water where they settle down in deeper part (e.g., Reineck and Singh, 1980; Araby and Motilib, 1999). As a whole, presence of trough and tabular cross-beds, parallel lamination and occasional swaley-type cross-beds indicate deposition in upper shore-face (e.g., Storms et.al., 2005).

Pebbly sandstone suggests its deposition in a distributary channel of prograding gravelly and sandy coastal environment. This facies formed probably by winnowing of pebble-bearing sands under agitating conditions. Similar accumulation of pebbles has been interpreted as a lag deposit winnowed by strong storm surges (e.g., Richards, 1986; Lindsey and Gaylord, 1992). As a whole facies assemblage D represents deposition under wave and storm action in a shoreface. Further, general lack of herring-bone structures, which are believed to be diagnostic feature of tidally influenced shallow marine and coastal deposits, again indicates a wave dominated and/or storm-dominated shoreface environment.

Shoreface sediments are controlled to a large degree by waves and wave induced currents. Shoreface sands down to a depth of 10 to 20 m below mean sea level, where normal wave action ceases. These sands generally exhibit decreasing grain size with growing water depth. While the upper shoreface deposits may contain gravelly sands and display multi-directional sedimentary structures (trough cross-beds and low angle tabular cross-beds), the lower ones consist of fine to very fine-grained sand. Here, the primary sedimentary structures consist mainly of planar laminated and small scale cross-beds. The bed forms and internal sedimentary structure along the beach-shoreface profile reflects transformation of deep water waves (oscillatory flow) to shoaling waves, generating land directed flow and return flow into the foreshore zone under upper flow regime conditions.

At depths or near fair weather wave base, long-crested symmetrical wave ripples, produced earlier by rare storm waves are bioturbated during normal fair weather condition. Landward this inactive ripples pass into active ripples which become increasingly asymmetric. There are associated with small or large scale cross-bedding. On the inner shelf and parts of the outer shelf, either hummocky cross-startified sand layers or thinner graded sandy and silty beds with cross stratified and sometimes with ripple tops are typical. At greater water depths on the outer shelf, the current component of the combined storm flow becomes dominant, leading to current rippled fine sand and silt beds.

FACIES RELATIONSHIP AND DEPOSITIONAL ENVIRONMENTS

The basic idea of Facies analysis is to recognize how different depositional environments are expressed by the development of characteristic structures, lithology and organic components in sedimentary rocks. The usual way to reconstruct the depositional history of an area is to group strata into facies assemblages; that is, measuring numerous stratigraphic sections, examining the rocks, and assigning those rocks a depositional environment based on sedimentary structures, paleontological evidence, if any and lithology. When this has been accomplished, the measured sections are correlated using the facies assemblages; and three dimensional models of deposition are constructed.

In the study area, i.e., Bayana Basin, rocks of Delhi Supergroup are exposed which comprise a heterogeneous assemblage of conglomerate, sandstones and shale; and exhibit lithofacies assemblages and sedimentary characteristics similar to a depositional environment which varies from fluvial to tidal to shoreface. In order to reconstruct the depositional setting of this Proterozoic sequence in the Bayana Basin, various sedimentary lithofacies, their assemblages and environment of deposition of each formation is discussed.

Nithar Formation

Stratigraphically, Nithar is the oldest formation of Delhi Supergroup in the area. The formation is characterized by three distinct lithologies, sandstones at the base, followed by shale and conglomerate. Interbedded sandstone and shale occurs in the lower part while interbedded clast-supported conglomerate and massive sandstone at middle part and finally parallel laminated and cross-bedded sandstone occurs at the upper part of the formation. Sandstones are medium to fine-grained, gritty at the basal part but massive in the middle part. Shale is red in color, faintly laminated. Conglomerate is clast-supported. Total eight lithofacies are evident in this formation, namely, clast-supported conglomerate, tabular cross-bedded sandstone, parallel laminated sandstone, interbedded shale and sandstone, ripple-bedded sandstone, Herring-bone cross-bedded sandstone and massive sandstones. All theses facies are assignable to two facies assemblages, i.e., Facies Assemblage A (tidally influenced fluvial deposit) and Facies Assemblage B (intertidal/tidal flat deposits). Table 4 and Figure 17 summarize the sedimentary features and interpretation of each facies of the Nithar Formation.

In the basal part of the Nithar Formation, finer assemblage of shale with faint lamination, interbedded with gritty to massive sandstone unit represents facies assemblage B, indicating deposition under an intertidal zone of tidal flat regime. The unit is nearly 14 m thick. Beds internally show thick-and-thin nature which implies influence of ebb and flood tidal currents. Overlying interbedded facies of clast-supported conglomerate with massive to parallel laminated sandstones with a thickness of approx. 7m, represents facies assemblage A; tidally influenced fluvial deposits, deposited in tidal estuary environment. The upper 9.5 m of this formation consists of sandstone beds exhibiting sedimentary features like tabular cross-beds, herring-bone cross-sets, symmetrical ripple-marks and parallel lamination. This sandstone unit represents facies assemblage B, i.e., deposits of intertidal environment. Azimuths of tabular cross-beds reflect north-east directed sediment transport indicating influence of across-slope current.

As a whole, quadrimodal palaeocurrent pattern indicates dispersal of sediments by diverse current systems, so typical of a coastal environment. The dominance of the influence of tidal features as well as the presence of storm and wave related currents to the sedimentation of the Nithar Formation, are suggestive of a tidal regime of intertidal to tidal estuary with intervening fluvial sedimentation. Vertical facies transitions from tidal to fluvial and back to the tidal environment indicate regressive succession with intervening transgressive period in the area.

Table 4. Description of lithofacies of Nithar Formation

Facies	Description	Facies Assemblage	Environment
Clast-supported conglomerate *(Facies Gc)*	Thick-bedded, Earthy to brown, rounded to subrounded clast of quartzite and quartz. matrix is coarse sand and granules of quartz.	FA:A, occurs interbedded with Sm & Sl facies	Tidally influenced fluvial deposits, in tidal estuary setting.
Tabular cross-bedded sandstone *(Facies Sp)*	Yellow to brown, medium to fine-grained, poorly sorted, show decrease in grain size Cross-sets are small scale and low angle.	FA:B, associated with Sr & S-hb facies	Deposits of intertidal zone of tidal flat
Parallel laminated sandstone *(Facies Sl)*	Medium-grained, moderately sorted, millimeter-scale laminae.	FA:B, interbedded with Fm facies	
Red shale *(Fm)*	Red in color, faintly laminated	FA:B, interbedded with Sl & Sm facies	
Interbedded shale and sandstone *(Facies Fm-S)*	Sandstones is medium to fine-grained, gritty in places, thinly bedded	FA:B	
Ripple-bedded sandstone *(Facies Sr)*	Thick-and-thin bedded medium-grained sandstones. Abundant symmetrical ripple marks.	FA:B, associated with Sp & S-hb facies	
Herring-bone cross-bedded sandstone *(Facies S-hb)*	Medium-grained, hard and compact sandstones, thick-and-thin bedded.	FA:B, associated with Sp & Sr facies	
Massive sandstones *(Facies Sm)*	Thick-bedded, medium to coarse-grained sandstones.	FA:B, associated with Gc facies	

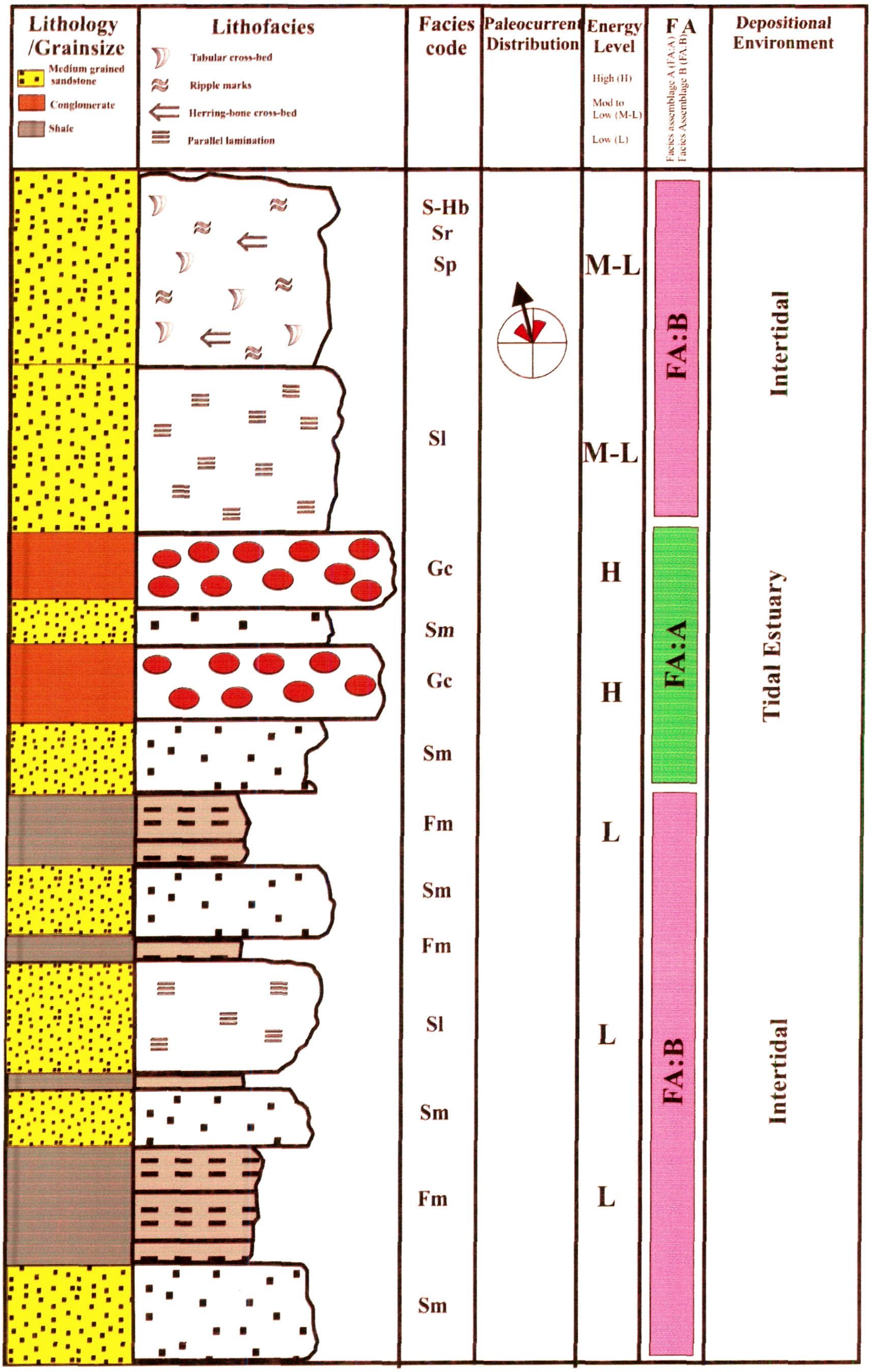


Figure 17. Diagrammatic representation of lithofacies & their depositional environments in Nithar Formation

Jahaj-Govindpura volcanic Formation

Jahaj-Govindpura volcanic Formation is represented by 29 m thick outcrop in the study area, which stratigraphically overlies the Nithar Formation. Lithologically it consists of medium to fine-grained, hard and compact, thick-bedded dark grey colored sandstones with features of volcanoclastic deposits like tuff, bomb, agglomerate, spatter etc., which are present throughout the section. Uppermost part of the section is pebbly and exhibits sets of tabular cross-beds and parallel lamination. Tuffacious sandstone is the dominant lithofacies in this formation.

Volcano-sedimentary succession of Jahaj-Govindpura volcanic Formation suggests the records of a phase of volcanism, followed by cooling and subsidence with associated siliciclastic sedimentation. Tuffacious sandstone with structures like tuff, agglomerate, volcanic bomb and spatter are suggestive of deposition under sub-aerial non-marine environment. This thick unit of sandstones, which interbeds the volcanoclastics, can be interpreted as a product of outpouring of volcanics, which followed the post-Nithar sedimentation (e.g., Singh, 1988). Uppermost part of the formation consisting of tabular cross-bedded and parallel laminated sandstone facies that can be interpreted as deposits of intertidal environment. The palaeocurrent direction of foresets of tabular cross-beds indicates offshore and longshore sediment dispersal. Overall, sediments of the Jahaj-Govindpura volcanic formation can be interpreted as deposition in an intertidal environment with intervening volcanism (Figure 18).

Jogipura Formation

The Jogipura Formation comprises a 13m unit of interbedded conglomerate-sandstone facies at the lower part, followed by 18m thick facies sequence of cross-bedded, ripple-bedded and parallel laminated sandstones in the middle part which is overlain by 2m thick conglomerate facies interbedded with ripple-bedded sandstones. Conglomerate is hard and compact, thick-bedded and essentially matrix-supported. Conglomerate contains imbricated pebbles of vein quartz, quartzite and

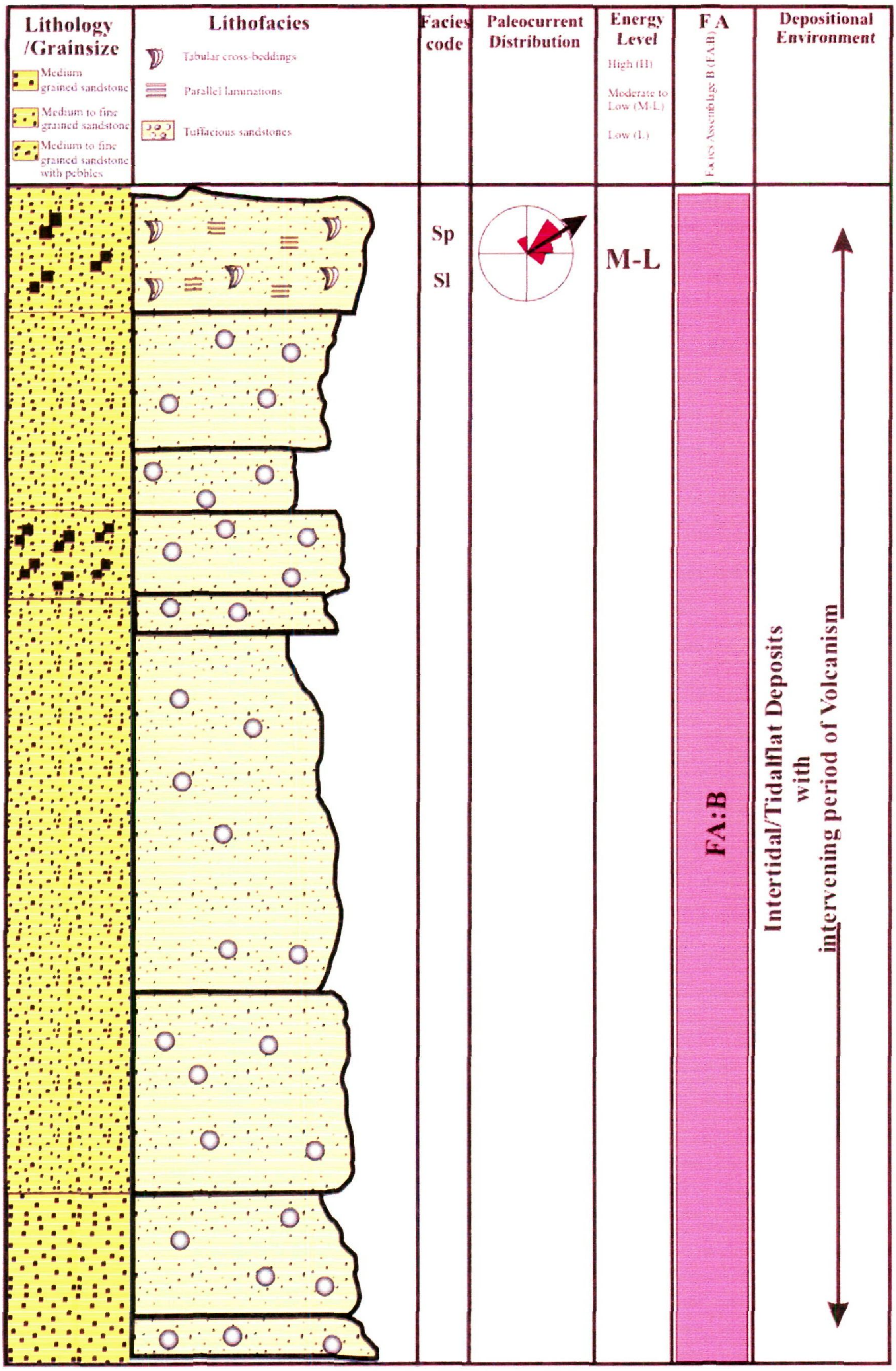


Figure 18. Diagrammatic representation of lithofacies & their depositional environments in Jahaj-Govindpura volcanic Formation

jasper. Sandstone is thick-bedded, medium-grained and pebbly in places. Pebbles show upward decrease in grain size. Total 4 lithofacies (Table 5) are observed in this formation, which are organized into two facies assemblages:- (Figure 19) the tidally influenced fluvial deposit (Facies Assemblage A) and the tidal flat/intertidal deposit (Facies assemblage B). The facies assemblage of tidally influenced fluvial deposit is characterized by interbedded sequence of matrix-supported conglomerate with medium to pebbly sandstones. The Intertidal facies assemblage consists of small-scale tabular cross-bedded sandstone, parallel laminated sandstone and ripple-bedded sandstone. The ripples are asymmetrical but interference ripple marks are also present in the middle part of the formation. The foresets of tabular cross-beds and ripple marks display bimodal palaeocurrent direction which indicates northward offshore as well as west-north-west longshore sediment dispersal pattern.

The lithofacies assemblages and palaeocurrent data provide a picture that the sediments of Jogipura Formation were deposited under two depositional environments, an is intertidal zone of a tidal flat and a tidal estuary where fluvial deposits were modified by tidal processes leading to tidally influenced fluvial deposits. However, the processes which produced tidally influenced fluvial deposits at the lowermost and uppermost part of the formation are the dominant ones; with an intervening episode of current systems which gave rise to intertidal deposits in the middle part of the formation. This vertical facies transition reflects the works of alternate energy system related to different episodes of transgression and consecutive regression acting upon the area.

Badalgarh Formation

In Badalgarh Formation two outcrop sections are studied, one 16m thick section in Bhagrain locality (Figure 20) and another 23m thick section in Alapuri locality (Figure 21). Sandstone is the only lithology for both the sections but lithologically sandstones of both the sections varies from each other. Sandstones of Bhagrain locality are medium to coarse-grained, thick-bedded, hard and compact, pinkish in color; while sandstones of Alapuri locality are fine-grained, thin-to-thick-bedded and brownish to white in color. Two lithofacies are identified on the basis of

Table 5. Description of lithofacies of Jogipura Formation

Facies	Description	Facies Assemblage	Environment
Matrix-supported conglomerate *(Facies Gc)*	Thick-bedded, brownish to pale yellow to black. Pebbles of vein quartz, quartzite, jasper. Hard and compact.	FA:A, occurs interbedded with Sp & Sr & Sl facies	Tidally influenced fluvial deposits, in tidal estuary setting.
Tabular cross-bedded sandstone *(Facies Sp)*	Sandstones are medium-grained, pebbly, cross-sets are small scale and low angle.	FA:B, associated with Gc, Sr & Sl facies	Deposits of intertidal zone of tidal flat
Parallel laminated sandstone *(Facies Sl)*	Medium-grained, pink colored, thick-bedded.	FA:B, interbedded with Gc, Sp & Sr facies	
Ripple-bedded sandstone *(Facies Sr)*	Asymmetrical & interference ripple marks	FA:B,D associated with Sp & S-hb facies	

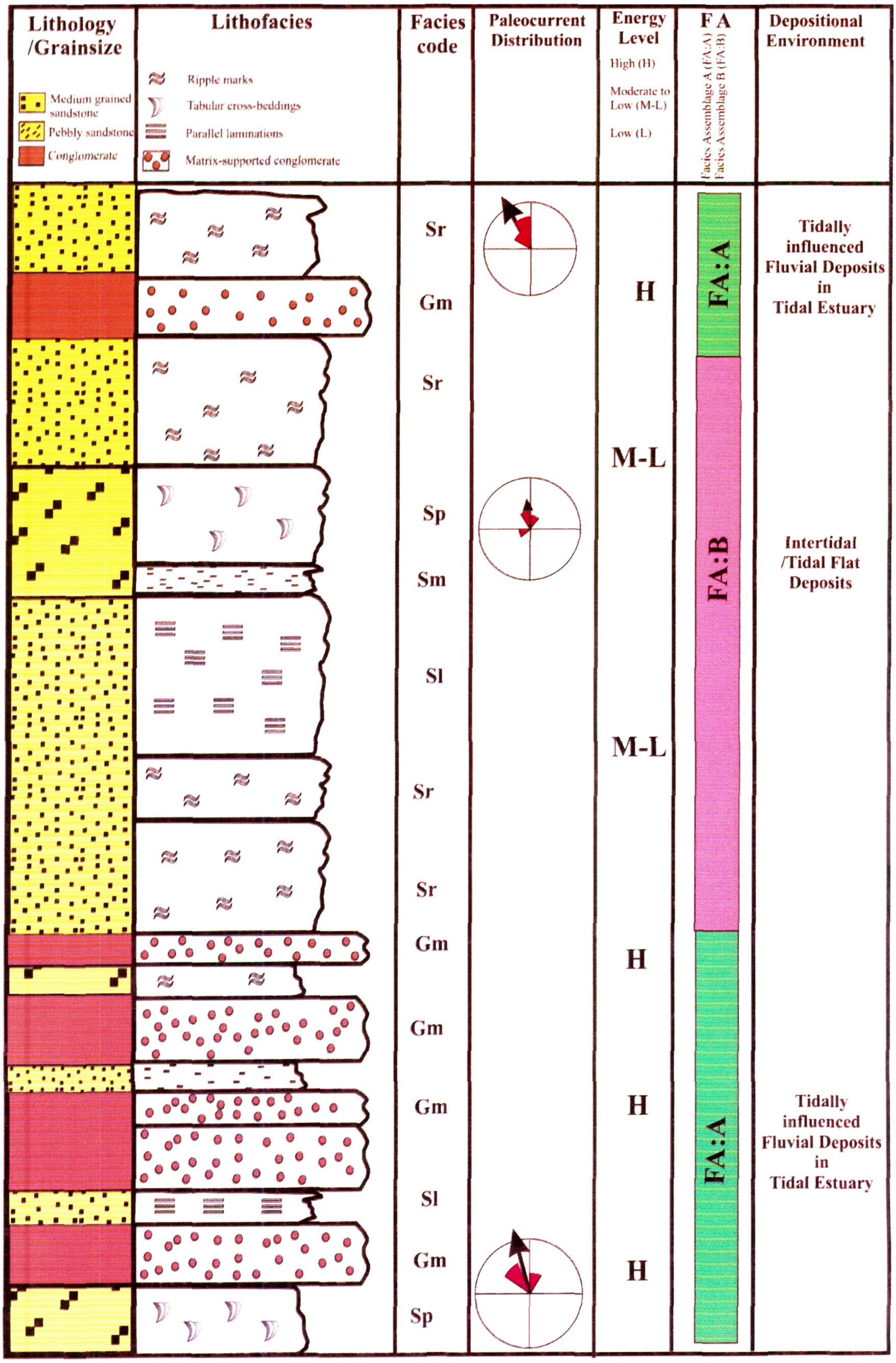


Figure 19. Diagrammatic representation of lithofacies & their depositional environments in Jogipura Formation

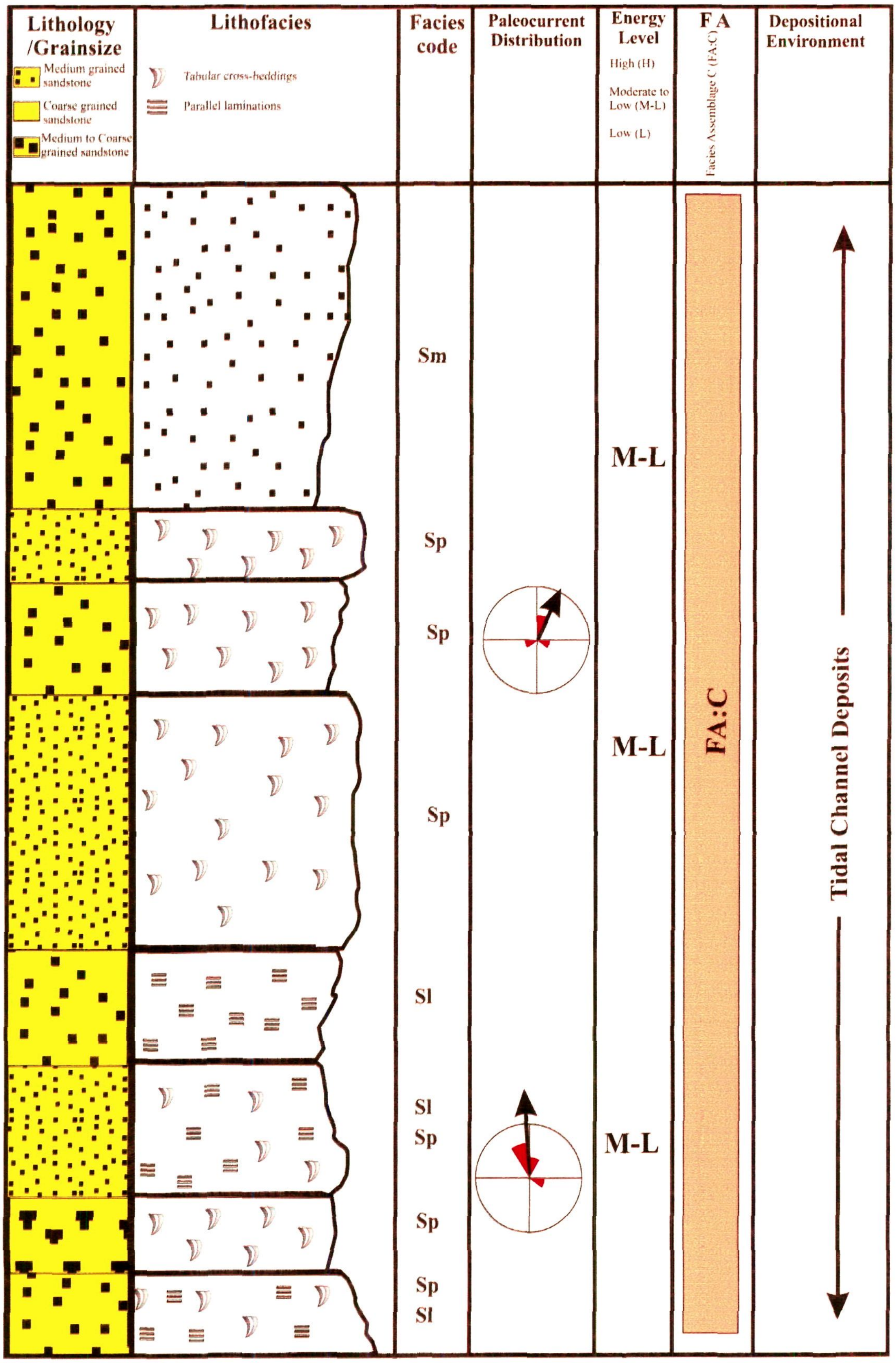


Figure 20. Diagrammatic representation of lithofacies & their depositional environments in Bhagrain locality of Badalgarh Formation

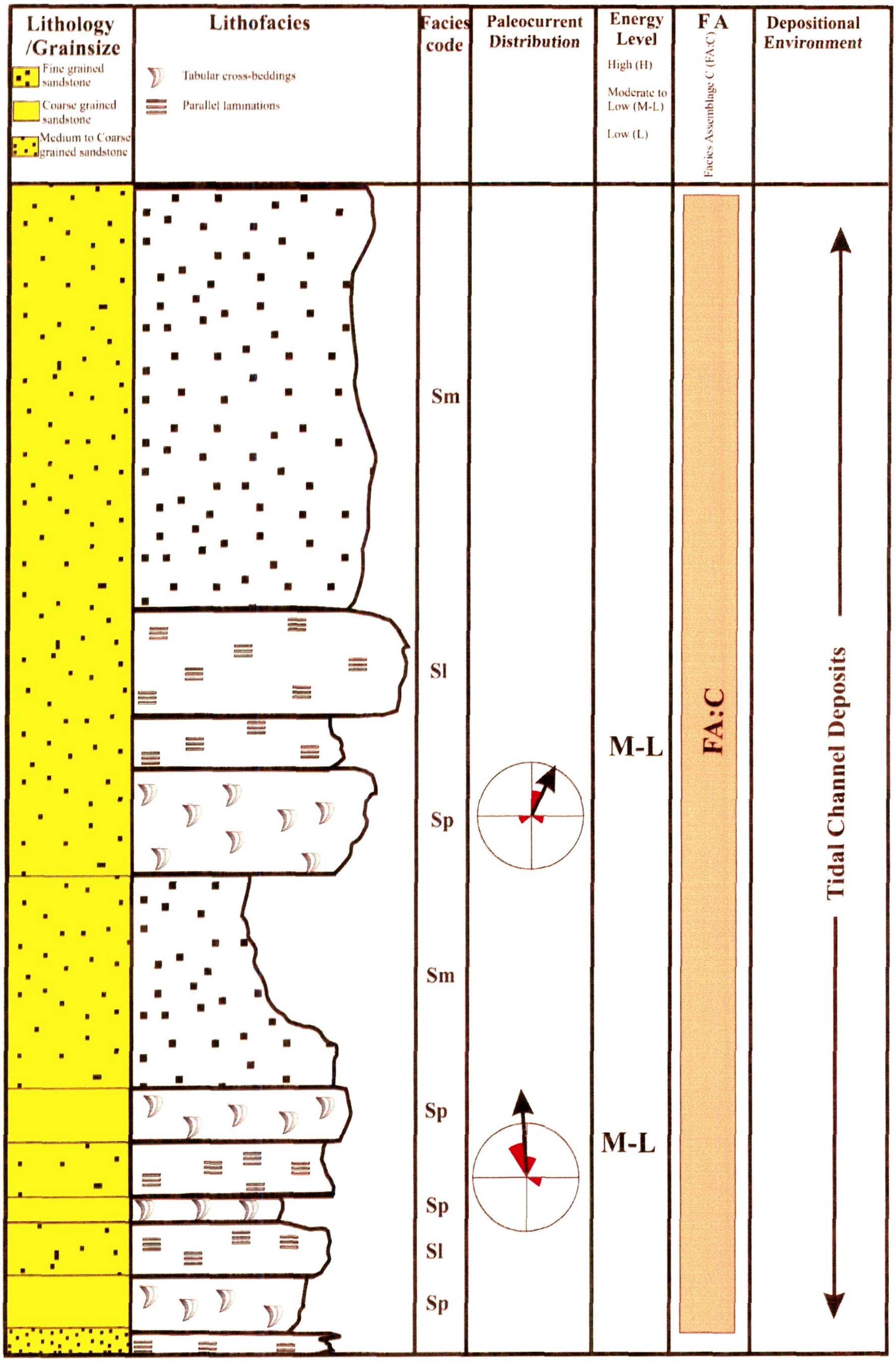


Figure 21. Diagrammatic representation of lithofacies & their depositional environments in Alapuri locality of Badalgarh Formation

sedimentary structures; (Table 6) large scale tabular cross-bedded and parallel laminated sandstone facies. Parallel laminations are associated with these cross-bedded sandstones. The formation shows vertically fining/thinning upward trend. Lithofacies are assigned to Facies Assemblage C, which represents deposits of tidal channel.

Some significant features are well observed in the outcrop of both localities. One is that large-scale tabular cross-bedded coarse-grained sandstones are arranged in an alternate sequence with medium to fine-grained parallel laminated sandstones.

Likewise, thick-bedded and thin-bedded sandstones are arranged in an alternate manner. Thick-and-thin bundle sequence of the facies suggests ebb-flood tidal cycles (Yang and Nio, 1985). These arrangements clearly indicate alternate high and low energy currents acting upon them. Significantly this arrangement is observed only upto upper middle part of the outcrop. In both localities, uppermost part of the formation is represented by thick-bedded massive sandstones which are devoid of any sedimentary structure. Presence of massive sandstones in the uppermost part suggests rapid deposition under tidal influence. Trimodal orientation of palaeocurrent direction in this formation indicates involvement of offshore and west-north-west as well as east-north-east longshore current in sediment dispersal. Overall, fining/thinning upward trend in the formation indicates deposition within channels.

Bayana Formation

Two lithostratigraphic sections are measured in Bayana and Bhimnagar localities of Bayana Formation. The Bayana outcrop is represented by 85 m thick alternate sequence of conglomerate and sandstones (Figure 22), whereas, Bhimnagar (Figure 23) represents 20 m thick outcrop of sandstones. In Bayana section, conglomerate is matrix-supported, hard and compact, with maximum size of clasts upto 2 cm. The clast size within conglomerate decreases upward. The sandstone is medium to fine-grained, hard and compact, with wavy contacts. Sandstones exhibit sedimentary structures like, lamination, large scale tabular cross-beds, herring-bone

Table 6. Description of lithofacies of Badalgarh Formation

Facies	Description	Facies Assemblage	Environment
Tabular cross-bedded sandstone *(Facies Sp)*	Medium to coarse-grained, hard and compact, large scale cross-beds.	FA:C, associated with Sl facies	Tidal channel deposits
Parallel laminated sandstone *(Facies Sl)*	Medium to fine-grained, hard & compact, thick-bedded.	FA:C, associated with Sp facies	

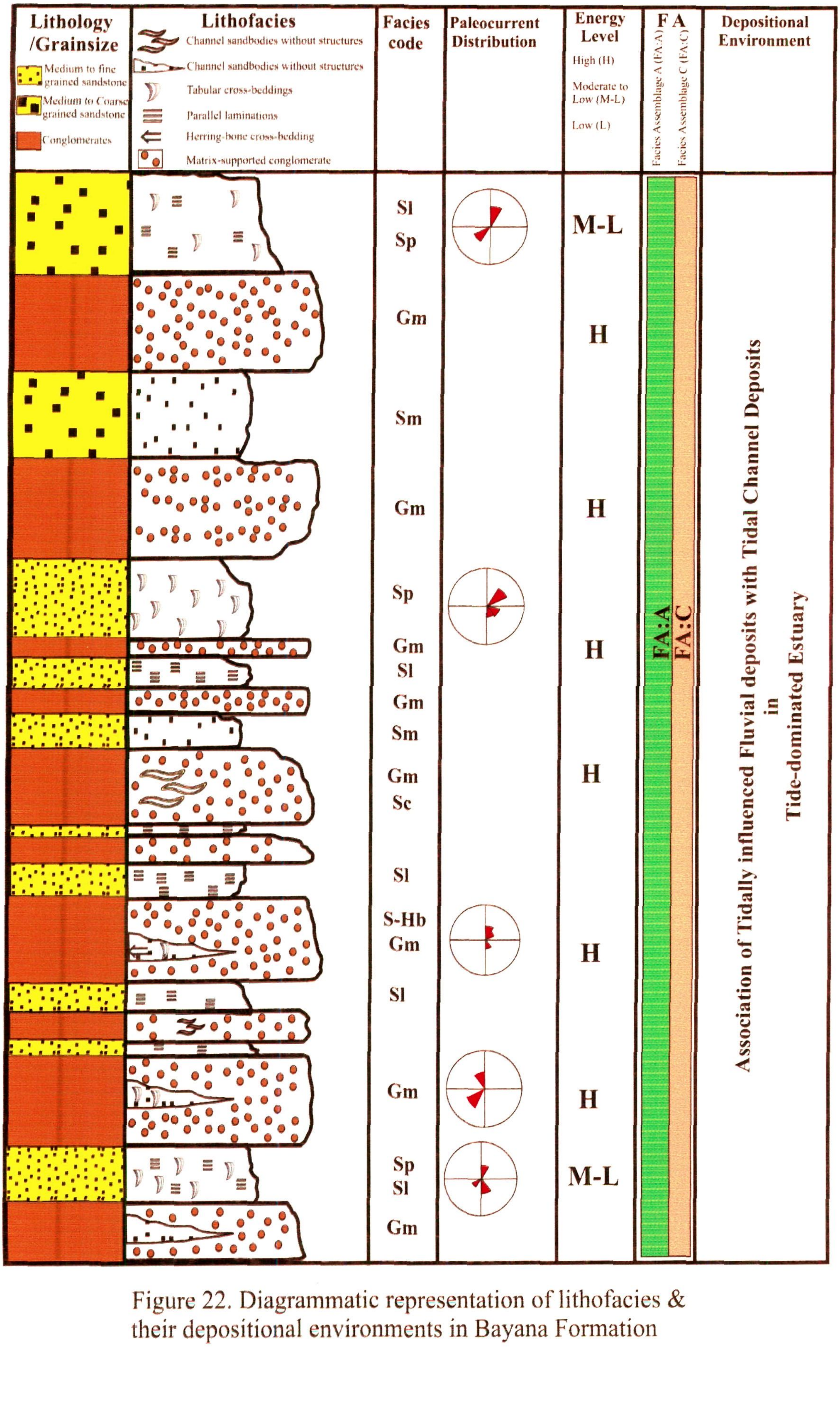


Figure 22. Diagrammatic representation of lithofacies & their depositional environments in Bayana Formation

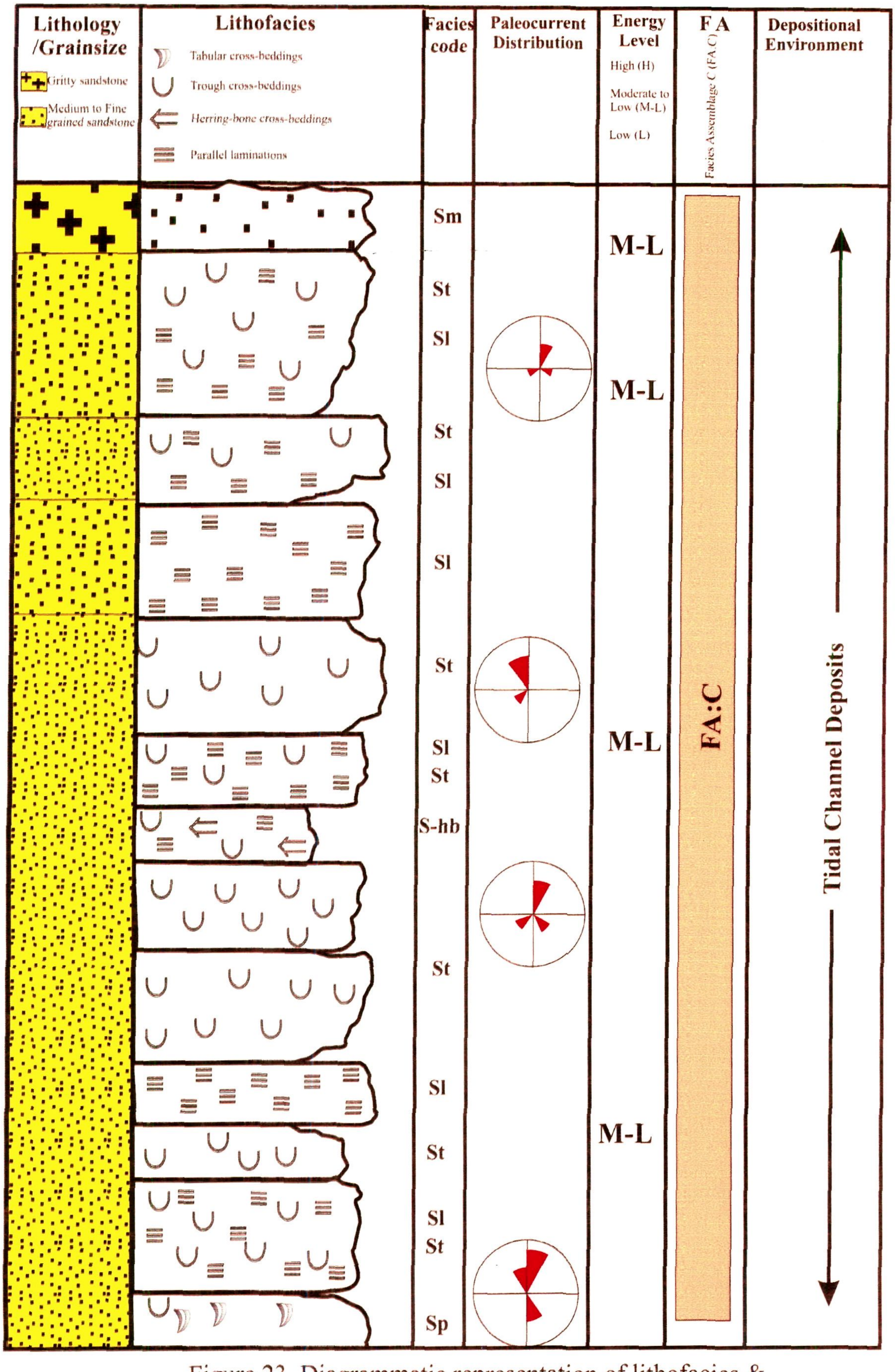


Figure 23. Diagrammatic representation of lithofacies & their depositional environments in Bhimnagar locality of Bayana Formation

cross-beds etc. In Bhimnagar locality, sandstones are medium to fine-grained, gritty and massive in upper part with large scale trough cross-bedding. Other features are parallel laminations, tabular cross-beds, herring-bone cross-beds etc. Total six lithofacies are identified in Bayana Formation which are grouped into two facies assemblages. Lithofacies of Bayana Formation are described in Table 7.

In Bayana locality, two facies assemblages are interpreted to be associated with each other. Facies assemblage A, which represents tidally influenced fluvial deposits, consists of interbedded sequence of matrix-supported conglomerate and large-scale tabular cross-bedded sandstones throughout the whole section as well as herring-bone cross-beds in basal and lower-middle part of the section. This assemblage is found to be closely associated with Facies assemblage C, represented by lithofacies like channel sandstone bodies and parallel laminated sandstones, interpreted to be tidal channel deposits. In the lower part of the section, thick beds of matrix-supported conglomerate is intercalated with thin beds of tabular cross-bedded and herring-bone cross-bedded sandstones. Parallel-laminated sandstone beds are also found to be interbedded with thick conglomerate beds. Number of channel sandstone bodies is observed from basal part to middle part of the section. They are present within thick-bedded, hard and compact matrix-supported conglomerate and consist of subangular quartzite clasts. The axis of the channel bodies varies from N 220^0 to N350^0. Some of them exhibit structures like herring-bone and tabular cross-beds, laminations and mild cracks.

Lithofacies which are observed in Bhimnagar locality are large scale trough cross-bedded sandstone, and parallel laminated sandstones, tabular cross-beds in the lowermost part and herring-bone cross-beds in the middle part of the outcrop. These facies can be grouped into facies assemblage C, representing tidal channel deposits. Abundant large scale trough cross-beds indicate lateral migration of sand-dunes of tidal channel bars. Occasional occurrence of herring-bone cross-beds suggests bed-load deposition by reversing tidal currents.

As a whole, association of the tidally influenced fluvial deposits with tidal channel deposits in the Bayana Formation suggests deposition of the sediments in a tide-dominated estuary. Presence of herring-bone cross-beds and tabular cross-beds

Table 7. Lithofacies of Bayana Formation

Facies	Description	Facies Assemblage	Environment
Matrix-supported conglomerate *(Facies Gm)*	Blackish brown, hard and compact, contain scattered pebbles. The maximum size of the individual clast is 2 cm.	FA:A, interbedded with Sp, Sl & Sc facies	Tidally influenced fluvial deposits
Tabular cross-bedded sandstone *(Facies Sp)*	Medium to coarse-grained, purple colored, large scale cross-sets,	FA:A, associated with St & Sl facies	
Trough cross-bedded sandstone *(Facies St)*	Medium to fine-grained, pink, laminated, large scale cross-beds.	FA:A, associated with Sp & Sl	
Herring-bone cross-bedded sandstone *(Facies S-hb)*	Occasional occurrence within channel sandstones	FA:A, associated with Gm, Sc facies	
Channel sandstones *(Facies Sc)*	Abundant, associated with conglomerate beds.	FA:C, associated with Gm facies	Tidal channel deposits
Parallel laminated sandstone *(Facies Sl)*	Medium to fine-grained, compact	FA:C, associated with Sp & St facies	

in channel sandstone alongwith their orientation suggest dominant tidal action upon them. Dominance of wavy contacts indicates presence of oscillatory flow. Palaeocurrent study of Bayana Formation displays two dominant sediment dispersal directions i.e., offshore and onshore direction, indicating reversal of current which is a characteristic feature of tidal environment. It suggests landward and basinward dispersal of sediments by both flood and ebb current. A possible depositional setting that can be suggested for this area is that fluvially derived sediments were modified in an estuary setting by shallow-marine processes.

Damdama Formation

In Damdama Formation, study of lithofacies was carried out in two outcrops; exposed in Umraind and Kanawar localities of the area. Outcrop in Umraind locality (Figure 24) consists of 32m thick section of medium to coarse-grained, hard and compact, gritty to pebbly sandstones which occasionally interbeds with thin-bedded matrix-supported conglomerate in lower and middle part of the section. Kanawar outcrop (Figure 25) is 14m thick and is represented by medium-grained, hard and compact thick-bedded sandstones. Total 8 lithofacies (Table 8) are identified in Damdama Formation which are assigned to three facies assemblages.

Lithofacies observed in Umraind section is as follows: thick-bedded, massive sandstone beds in the lowermost part and in the middle part which interbeds with thin-bedded matrix-supported conglomerate. This facies represents facies assemblage A (tidally influenced fluvial deposits). Between these two units, lies a unit of medium-grained sandstones containing large scale tabular cross-beds and channel sandbodies; which can be assigned to facies assemblage C (tidal channel deposits). Upper part of the section is represented by facies assemblage D (shoreface deposits), which is characterized by gritty to pebbly sandstones showing large scale tabular cross-beds, trough cross-beds, swaley-type cross-beds, and hummocky cross-beds. Dominance of tabular and trough cross beds and occasional occurrence of swaley-type trough cross-bed indicate deposition in upper shoreface (e.g., Storms et.al., 2005). Absence of herring-bone cross-beds indicates a wave dominated or storm- dominated shoreface environment. This is further confirmed by occurrence of hummocky cross-bedded sandstone which is a diagnostic feature of

Table 8. Description of lithofacies of Damdama Formation

Facies	Description	Facies Assemblage	Environment
Matrix-supported conglomerate *(Facies Gm)*	Light brown, poorly sorted, clast of vein quartz, quartzites, max. size upto 32mm	FA:A, associated with Sm & Sp facies	Tidally influenced fluvial deposits
Tabular cross-bedded sandstone *(Facies Sp)*	Medium-grained, thick-bedded, pebbly in places, large scale cross-sets,	FA:A,C,D associated with St & Sl facies	
Channel sandstones *(Facies Sc)*	Pebbly sandstones, fine laminations	FA:C, associated with Sp, St & Sr facies	Tidal Channel deposits
Ripple-bedded sandstones *(Facies Sr)*	Thick-bedded, medium-grained sandstones, abundant asymmetrical ripple marks	FA:D, associated with Sp, St & Sc facies	Wave & storm dominated deposits
Interference ripple-bedded sandstones	Thick-bedded, medium-grained sandstones	FA:D associated with Sr, & Sp facies	
Trough cross-bedded sandstone *(Facies St)*	Medium-grained, light brown, thick-bedded, large scale cross-beds.	FA: D associated with Sp, Sc & Sl	
Swaley-type trough cross-bedded sandstones	Light brown, medium-grained sandstones	FA:D associated with St facies	
Hummocky-cross-bedded sandstones *(Facies S-hc)*	Light brown medium-grained pebbly sandstones.	FA:D associated with Sp facies	

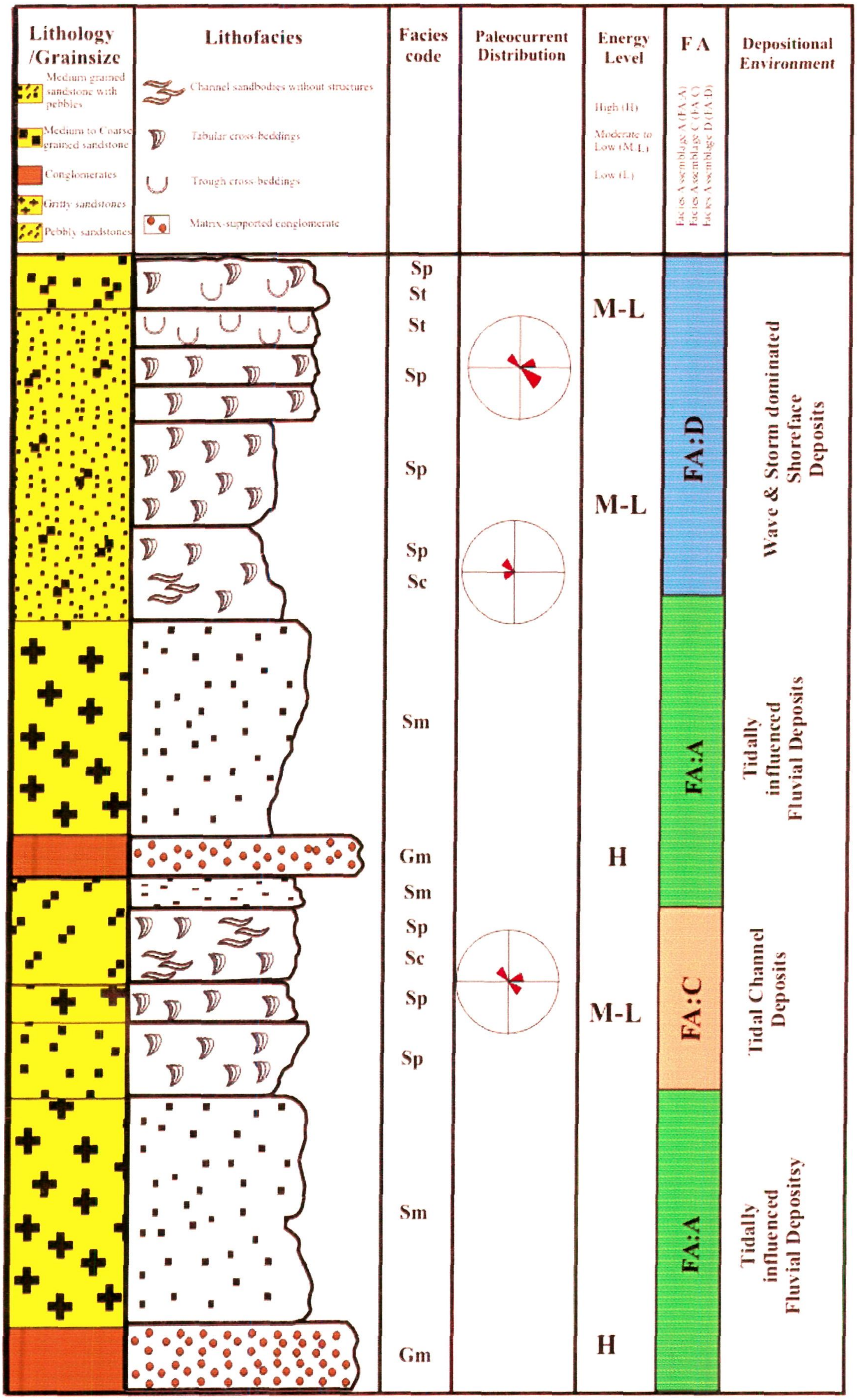


Figure 24. Diagrammatic representation of lithofacies & their depositional environments in Umraind locality of Damdama Formation

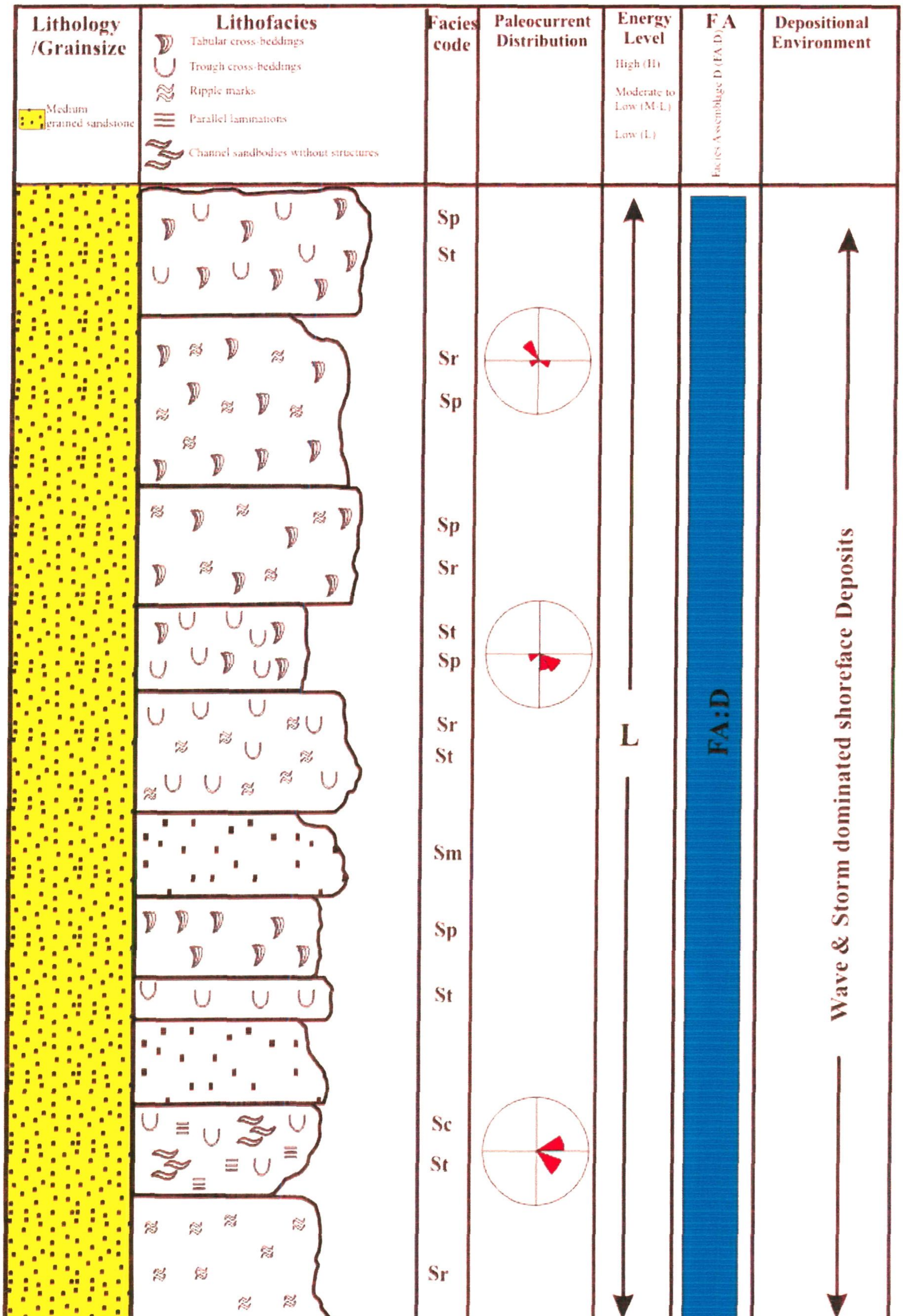


Figure 25. Diagrammatic representation of lithofacies & their depositional environments in Kanawar locality of Damdama Formation

stormy conditions. This facies suggests its deposition in a zone affected by storm waves and wind induced currents. General lack of ripples on the bed rules out reworking of the storm beds by fair -weather waves. Palaeocurrent study shows east-south-east longshore dispersal of sediment. However orientation of channel sandstone axis is parallel to onshore current .Therefore both ESE longshore and onshore currents were influential in this locality.

The arrangement of the lithofacies clearly indicates association of three facies assemblages, fluvial deposits influenced by tidal process in the lower and middle part, tidal channel deposits in the middle part and shoreface deposits in the upper part of the area. It can be suggested that fluvially derived sediments of this locality were further modified by shallow marine coastal processes under stormy condition in a lower to upper shoreface environment.

In Kanawar locality, lower part of the section is characterized by asymmetrical ripple-bedded sandstones and trough cross-bedded sandstones with occasional channel sandbodies. It is overlain by large scale tabular and trough cross-bedded, asymmetrical ripple-bedded and occasional interference ripple-bedded sandstone beds upto uppermost part. Lithofacies are assignable to facies assemblage D which represents wave and storm dominated shoreface deposits. Abundance of asymmetrical ripples and significant occurrence of interference ripple marks suggest a shallow water backshore-shoreface environment of deposition (e.g., Chauhan et.al. 2004). Large-scale. tabular and trough cross-beds indicate their deposition in upper shoreface environment (Storm et.al. 2005). The channel sandstones can be interpreted as deposit of shallow channels which were characterized by episodic fluctuation in flow velocity and were tidally influenced (e.g., Ahmad, 1988). Palaeocurrent direction in this locality suggests onshore flow of current direction. Axis of the channel is parallel to the main palaeocurrent direction.

Trimodal palaeocurrent pattern of overall Damdama Formation indicates dominance of east-south-east longshore current followed by west-north-west longshore current and onshore current. Lithofacies assemblages suggest tide-influenced fluvial deposition in the lower part of the formation, followed by tide-influenced shallow marine succession comprising of tidal channel assemblage in the mid part of the formation. After that, tidal deposition gradually terminated with rise of sea-level and these deposits are overlain by a wave and storm influenced shoreface deposits in the upper part of the formation.

Weir Formation

Stratigraphically, Weir Formation is the youngest formation in Delhi Supergroup. In study area it is represented by 18m thick outcrop of medium-grained, pink sandstones with wavy bed contacts. Lithofacies are included in facies assemblage D (wave and storm dominated shoreface deposits) which consists of large scale tabular and trough cross-bedded sandstones, asymmetrical ripple-bedded sandstones and parallel-laminated sandstones (Table 9 & Figure 26).

High angle trough cross-bedded sandstones oriented in current direction flowing parallel to shore are product of upper shoreface deposited by longshore current. Abundant asymmetrical ripples with crests oriented parallel to current direction are also an upper shoreface feature (e.g., Reading, 1978). Wavy nature of bedding indicates influence of oscillatory flow. Further dominant longshore orientation of palaeocurrent direction suggests an upper to lower shoreface environment for deposition of Weir Formation.

Sedimentation and Depositional History

Studied seven Mesoproterozoic formations of Bayana Basin comprise four main facies assemblages ascribed to tidally influenced fluvial deposits, tidal flat deposits, tidal channel deposits and wave and storm-dominated shoreface deposits. These contrasting palaeoenvironmental settings suggest deposition at a basin margin. Sediments were derived from fluvial as well as shallow marine sources. Fluvial deposits are limited, but tidal deposits are regionally extensive. Sediments were accumulated in tide-dominated estuary, in intertidal flat, in tidal channel, in wave-dominated shallow water environment as well as in storm-dominated upper to lower shoreface. Evidence of alternate episode of transgression and regression is well-documented in the study area. Also, primary sedimentary structures are mostly well-preserved. Although interpretation of tidal regime in terms of macro, meso or micro-tidal range is not easy, but the sandstones under description show many features which are indicative of macro-tidal environment. The 85 m thick outcrop

Table 9. Description of lithofacies of Weir Formation

Facies	Description	Facies Assemblage	Environment
Tabular cross-bedded sandstone *(Facies Sp)*	Medium-grained, pink sandstone large scale cross-sets	FA:D, associated with St & Sl facies	Wave & storm dominated Shoreface deposits
Trough cross-bedded sandstone *(Facies St)*	Medium-grained, pink sandstone large scale cross-beds, high-angle	FA:D, associated with Sp & Sl	
Ripple-bedded sandstones *(Facies Sr)*	Medium-grained, pink to white sandstone abundant asymmetrical ripple marks	FA:D, associated with Sp & Sl	
Parallel-laminated sandstones *(Facies Sl)*	Medium-grained, pink sandstone	FA:D, associated with Sp & Sr	

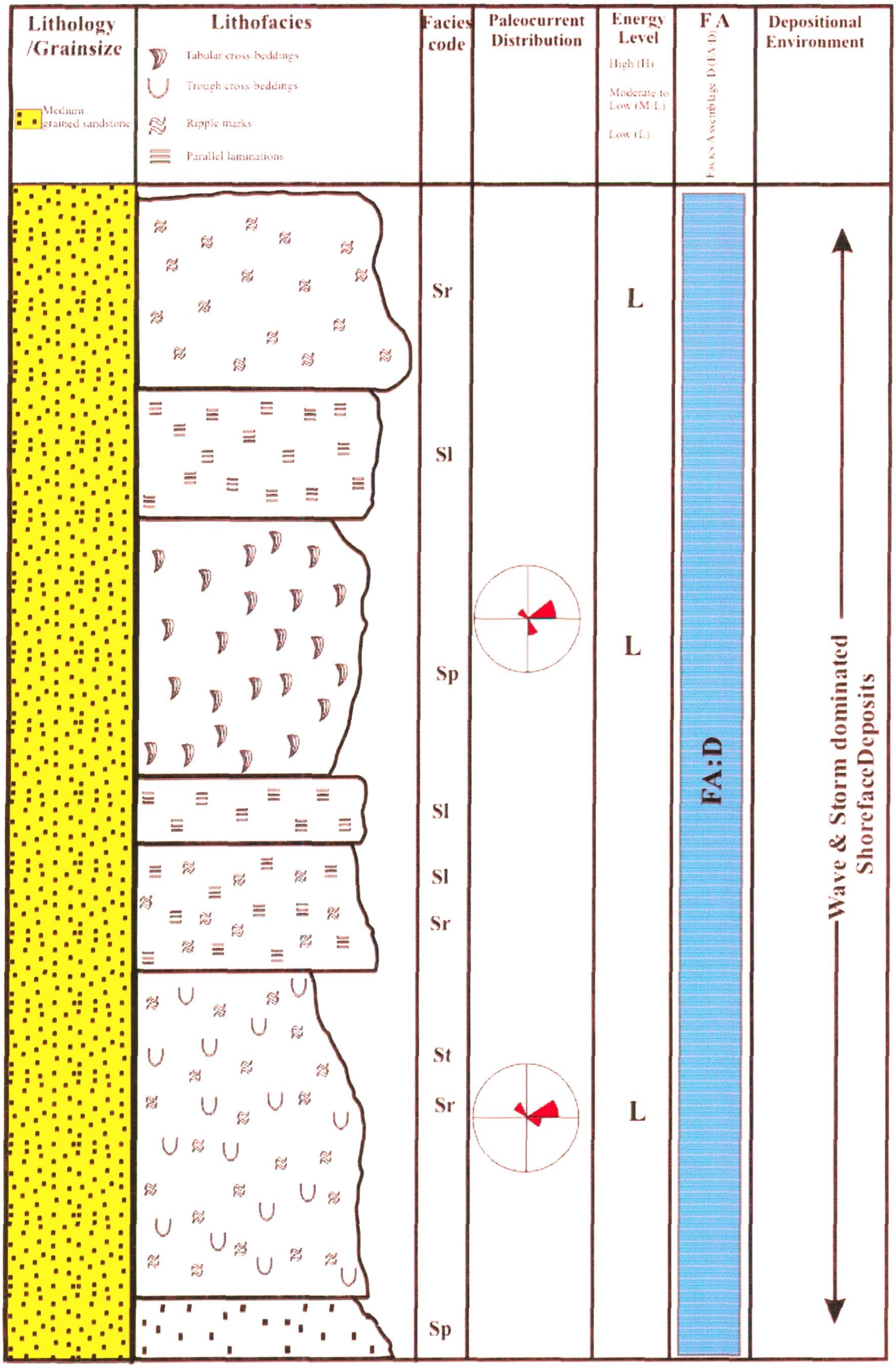


Figure 26. Diagrammatic representation of lithofacies & their depositional environments in Weir Formation

exposed in Bayana locality which represents fluvial deposits modified by tidal processes in tidal-estuary settings, indicates that coastline was macrotidal (>4 m), at least for some periods, and suggests a significant amount of sediment storage and also active sediment supply from a shallow marine source (e.g., Sultan and Bjorklund, 2006). Other features suggestive of macro-tidal environment are abundant parallel laminated sandstone facies, occasional occurrence of herring-bone cross-bedding, wavy bedding type as well as interbedded sand-shale sequences. Based on frequency and intensity of storms, shoreface can be classified into three types: strongly storm-dominated shorefaces (high energy), moderately storm-dominated shorefaces (intermediate energy), and weakly storm-affected shorefaces (low energy). Presence of hummocky cross-bedded sandstones in the study area suggests that shoreface deposits of Bayana Formation are strongly storm-dominated.

Delhi sediments and volcanics were deposited in a number of isolated structural basins or fossil grabens under diverse depositional conditions such as shallow water fluvial to marginal marine environments (e.g., Banerjee and Singh, 1977; Singh 1982, 1984, 1988). Bayana was one of the small sub-basins surrounded by Pre-Delhi rocks on its southern side from Aund to Bayana where initial phase of sedimentation started. Earlier study of the Delhi Supergroup rocks of Bayana Basin summarized by Singh (1991), suggests, that initial sedimentation started in this basin in two domains with two dispersal centres but later on they joined to form one domain having two dispersal centres. These sediments were laid down in coastal and associated environments under stable to unstable shelf tectonic framework with a moderate to high rate of subsidence. A phase of volcanism during Nithar time produced a sequence of basic volcanics which was subsequently reworked. Sedimentological studies of the basin-fills indicate WNW-ESE trend of shoreline, NNE palaeoslope along the basin length and NW and SE palaeoslope across it.

Through the present study, depositional history of the study area can be summarized as follows: initial sedimentation occurred in low-land area of the basin, during a rise in sea level, when shallow marine conditions were dominant, depositing the lower unit of Nithar Formation with finer assemblage of fine-grained sandstones interbedded with red shale unit. This phase is followed by subsequent fall in sea level which resulted in seaward translation of depositional environments and marked an end to the deposition of shallow marine shoreface deposits and beginning of fluvial sedimentation. Thus in upper part of Nithar Formation, a fluvial deposit of clast-supported conglomerate interbedded with sandstones duly influenced by tidal processes directly overlain the lower unit of shale-sandstones.

At the end of the deposition of Nithar Formation, a major change in environmental condition took place involving a phase of volcanism. Volcanoclastic detritus were eroded, transported to the basin and deposited; due to sediment gravity flow. This intermittent phase of volcanism marked the beginning of sedimentation of Jahaj-Govindpura volcanic Formation and was responsible for deposition of thick unit of tuffacious. Later on, the sediments were modified by tidal processes in an intertidal environment which form the uppermost unit of the formation consisting of tabular cross-bedded and parallel laminated sandstones facies.

Towards the end of deposition of Jahaj-Govindpura volcanic Formation, a fall in sea level caused a regressional phase, resulting in fluvial deposition in lowermost part of overlying Jogipura Formation which is represented by matrix-supported conglomerate beds interbedded with thin-bedded sandstones. Uppermost part of the same formation also bears the signature of fluvial sedimentation. However an intermediate unit of lithofacies suggesting their deposition in intertidal environment is also present in between these two regressive phases, which undoubtedly carries the evidence of an intermittent transgressive phase. During the early phase of deposition in overlying Badalgarh Formation, a rise in sea level resulted in marine transgression across the area and caused deposition of facies assemblage of tidal channel deposits in this formation. The upper part of this formation is characterized by rapid deposition under tidal processes which is represented by thick beds of massive sandstones. This transgression is succeeded by major regressive phase during early deposition of Bayana Formation, leading to thick deposition of fluvial deposit of matrix-supported conglomerate interbedded with sandstones in the lower part. Tidal influence is well-evident in this deposit and also in upper part of this formation which suggests its deposition by tidal processes in a tide-dominated estuary and in tidal channel bars during subsequent transgression. Overlying Damdama Formation shows deposition of thin beds of fluvial deposits in the lower part suggesting smaller phase of regression in the area. These deposits are gradually transmitted to tidal facies assemblage, which is again overlain by shoreface deposits representing a major phase of transgression in the area for a considerable period of time. Deposition under this transgression phase continued till the time of deposition of sediments of Weir Formation resulting in thick deposition of wave and storm dominated shoreface deposits.

In summary, it can be proposed that in Bayana Basin, sediments supplied during episodic transgressive and regressive phase were modified under tidal processes and later by wave and storm dominated processes in a shallow marine environment.

Depositional Model

Depositional models are summaries of sedimentary environments or systems, which can be used for comparison to other environments or systems. Depositional models provide a guide for future observations, evaluate the validity of existing concepts, and can be used as a tool for prediction of geologic situations with incomplete data (Walker, 1979; Miall, 1999). Models can be created from experimentation, simulation, theory, and the simplification of multiple observations from the study area.

The present study focuses on the framework in which the processes took place that are responsible for the deposition of Bayana Basin sediments. The objective is the development of a model that will improve the understanding of the genesis of lithofacies formed under these conditions, facilitate their recognition in the field, and deepen the insight into the depositional processes that play a part in their formation. Thus a conceptual model has been constructed to provide an idea about the paleogeography and environments of deposition of the study area. Internal sedimentary structures, lithofacies, their interrelationship and association are taken into consideration for the interpretation of depositional model. This model will be used more as an explanatory tool than for predictive purposes.

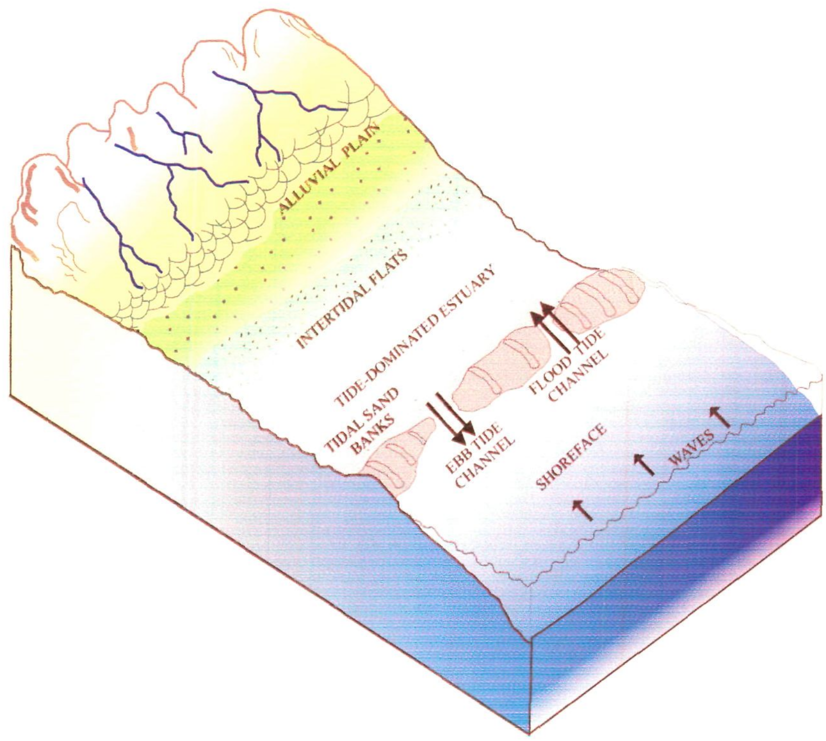


Figure 27. Diagrammatic representation of depositional environments of Bayana Basin

General model

Sediments carried out from the provenance by different agents were affected by a number of processes resulting into deposition of seven formations of Bayana Basin under two main environmental conditions; tidal as well as shoreface (Figure 27).

Sub-environments and energy conditions

Two main depositional environments. i.e., tidal and shoreface, which are considered to be existed in the study area, has sub-environments within them. For tidal environment, three sub-environments; viz., tidal estuary, tidal channel and tidal flat (intertidal) are interpreted on the basis of different characteristic facies assemblages and their association with one another. Shoreface environment is interpreted as wave-dominated as well as strongly storm dominated shoreface as it is evident from relationship of various lithofacies in the facies assemblages.

A distinct but gradual upward decrease in grainsize trend is observed in overall depositional pattern of all the studied formations in the study area. It indicates that energy conditions diminish upward. Based on this energy condition, again three sub-environments can be suggested; a lower sub-environment dominated by coarsest sediments, where mostly fluvial deposits affected by tidal processes are found, followed by a middle sub-environment dominated by coarse to medium-grained sand and finally overlain by an upper sub-environment where energy condition decreases and which mainly accommodated fine-grained sands and finer assemblages. In all three energy domains, sediments differ in terms of sedimentological characteristics (lithology, structures etc.) which reflect various transporting and depositional conditions.

Types of transport and sedimentation

Four types of transport mechanisms have been interpreted for the sediment transportation system in the study area. First type is identified as mass transport or **mass flows;** which is evident from the presence of clast-supported as well as matrix-supported conglomerate (debris-flow) deposits with frequent presence of significant size of clast, sizes decreasing upwards. Second type is **unchannelized flows,** which is responsible for deposition of more or less rhythmic/alternate succession of high and low energy facies units like alternate beds of coarse-grained/medium to fine-grained sandstones, thick-bedded/ thin-bedded sandstones, interbedded sequence of shale-sandstone etc. Third type of transport system that is suggested is through **channelized flows.** Deposits resulted from channelized flow system are facies like channel sandbodies, large scale bidirectional large scale cross-beds, parallel lamination, ripple marks etc. Last type is interpreted as **settling from suspension**; which represents deposition of red shale.

Present approach to study the sedimentation history is based on the concept that modern depositional environments provide the 'key to the past' when analyzing them. Further work is required on these facies for reconstruction of a much realistic modelfor the basin.

Texture

CHAPTER - IV

TEXTURE

The textural study of grain-size, roundness and sphericity allows unequivocal identification of transporting agents and depositional setting. According to Suttner (1974), textures of the rock reflect their provenance characteristics, depositional environment and diagenesis. A large number of early workers have made contributions to grain size studies including Udden (1898, 1914), Wentworth (1922, 1929), Trask (1932), Krumbein and Pettijohn (1938) and Otto (1939). In his classical study, Doeglas (1946) demonstrated that grain size distributions are mixture of two or more populations produced by varying transport conditions. He developed an empirical classification of curves to specific sedimentary environments.

Folk and Ward (1957), Mason and Folk (1958), Friedman (1961, 1962) carried out detailed study of sedimentary textures. They employed bivarient analysis involving the use of size parameters in various combinations as environment indicators. The environment of deposition using various statistical parameters of sediment distribution and their relationship with hydrodynamic conditions has been studied by Duane (1964).

Friedman (1967) established the use of two component (bivarient) diagrams that plot one statistical parameter against another for recognition of sandstone types. Visher (1969) and his co-workers demonstrated that each cumulative curve comprises a number of straight line segments of different slopes which represent truncated log-Gaussian sub-populations.

The Delhi Supergroup sandstones of Bayana Basin were studied for their textural attributes to interpret their provenance, environment of deposition, diagenesis and estimating the influence of texture on detrital modes and petrofacies. Their interrelationships were studied using bivarient plots.

METHODS OF STUDY AND DATA PRESENTATION

Thin sections were used in this study for grain size analysis and estimation of roundness as well as sphericity. Thin sections showing the least modification of textures by diagenesis and compaction effects were selected. These screening constraints restricted the textural study to 106 samples of sandstones out of total 519 samples collected from the study area during number of field visits.

Grain size measurement was carried out using Chaye's point-counting technique (1949). About 300 grains were counted from each thin section. The present study employed Phi-scale which was introduced by Krumbein (1934). The size data was grouped into half Phi-scale intervals. The statistical parameters of grain size distribution were derived with the help of cumulative frequency curve plots. Cumulative frequency curves of grain size data were plotted on log probability paper. The grain diameter in Phi units represented by Φ 5, Φ 16, Φ 25, Φ 50, Φ 75, Φ 84 and Φ 95 percentiles were read from the size frequency curves. These values were then converted to their sieve equivalents with the help of Friedman's (1958) graph.

STATISTICAL PARAMETERS

Grain size: Various statistical parameters of grain size distribution like graphic mean (Mz), inclusive graphic standard deviation (σ I), inclusive graphic skewness (Ski) and graphic kurtosis (K_G) were computed using Folk's formulae (1980).

Graphic Mean (Mz): It is a function of the size range of available sediment and the amount of energy imported to the sediment which depends on current velocity or turbulence of the transporting medium. It is calculated with the help of Folk's formula:

$$Mz = (\Phi\ 16 + \Phi\ 50 + \Phi\ 84) / 3$$

Inclusive Graphic Standard Deviation (σI): It depends upon competency and stability of the current. Relatively constant strength currents produce very well sorted to well sorted sediments but fluctuating currents will give rise to poorly sorted sediments. This parameter is given by the formula:

$$\sigma I = (\Phi\ 84 - \Phi\ 16)] / 4 + [(\Phi\ 95 - \Phi\ 5) / 6.6$$

Inclusive Graphic Skewness (Ski): It measures the degree of asymmetry of the frequency distribution and is determined by the relative importance of the tails of the distribution. The skewness or asymmetry is also determined by the position of the mean with respect to median. Several formulae for computing skewness have been proposed. The most comprehensive formula is given below:

$$Ski = (\Phi 16 + \Phi 84 - 2\ \Phi 50) / 2(\Phi 84 - \Phi 16)\} + \{(\Phi 5 + \Phi 95 + 2\ \Phi 50) / 2(\Phi 95 + \Phi 5)$$

Graphic Kurtosis (K_G): Graphic kurtosis reflects the peaked-ness of the distribution and measures the ratio between sorting in the central portion. If the central portion is better sorted than the tails, the curve is said to be excessively peaked or leptokurtic. When tails are better sorted than the central portion, the curve is flat peaked and platykurtic. The graphic kurtosis is calculated with the help of the following formula:

$$K_G = (\Phi\ 95 - \Phi\ 5) / 2.44\ (\Phi\ 75 - \Phi\ 25)$$

Skewness and kurtosis were referred to as indicators of selective action of transporting agents by Krumbein and Pettijohn (1938). Folk and Ward (1957) suggested that sands deposited near the source are characteristically leptokurtic and positive-skewed. Mason and Folk (1958) made comparative textural studies of recent beach sands, dune and aeolian flat environments. These studies indicate that beach sands are normal or negative-skewed and leptokurtic, dune sands have positive skewness and are mesokurtic, and 'aeolian flat' sands are positively skewed and leptokurtic.

Roundness: Roundness of grains is a function of transportation process on the debris furnished by the source area. It reflects abrasion history, which in turn depends on the diverse geologic controls such as relief, kinds of source rock, distance and mechanism of transportation and mineralogy of the grains. Roundness was first quantitively measured by Wentworth (1922), who used the curvature of the sharpest corner. Later it was defined by Waddell (1932) as the average radius of curvature of all the corners divided by the radius of the largest inscribed circle. Now roundness values are obtained by comparison with photographic charts for sand grains. Scale used for measurement of roundness is as follows:

0.12 – 0.17	-	Very angular
0.17 - 0.25	-	Angular
0.25 – 0.35	-	Subangular
0.35 – 0.49	-	Subrounded
0.49 – 0.70	-	Rounded
0.70 – 1.0	-	Well rounded

Sphericity: It states quantitively how nearly equal the three dimensions of an object are. The most commonly used method of determining the sphericity is through visual comparison. For the present study the comparison chart given by Krumbein and Sloss (1963) was used for classification of sandstones into two classess; high sphericity and low sphericity.

> 0.9	-	High sphericity
< 0.3	-	Low sphericity

Bivarient plot of textural parameters: Bivarient plots are used to show the interrelationship of various textural attributes of the sandstones of Bayana Basin. Different textural parameters of sandstones are plotted against each other and their relationship is determined statistically by computing their correlation coefficient values. Different plots which are used include mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting.

NITHAR SANDSTONES
(Nithar Formation)

The graphic mean (Mz) of the sandstones of Nithar Formation ranges from 2.05 Φ to 2.53 Φ, average 2.3 Φ, indicating medium grain (Table 10) . σ I values range from 0.40 Φ to 0.82 Φ indicating moderately well sorted to moderately sorted, average is 0.64 Φ suggesting moderately well sorted. **Ski** ranges from – 0.09 to + 0.17, average being 0.57. The samples thus belong to fine skewed to near symmetrical. The graphic kurtosis values range from 0.79 to 1.72, average being 1.00. Most of the samples are platykurtic followed by mesokurtic and very leptokurtic. The sandstones have grain roundness ranging from subangular to rounded. In most of the samples, majority of the grains are subangular (average 46.5%) to subrounded (average 53.1%). The mean roundness of the individual samples range from 0.35 to 0.46, average being 0.37 (Table 11). The studied grains show low sphericity occupying 80.04 % while rest of the 19.96% is of high sphericity (Table 12). The mean sphericity values of the individual samples range from 0.36 to 0.50, average 0.41. Texturally, the studied sandstones are sub-mature having subangular to subrounded grains (Table 13). Clay is absent from the samples suggesting that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Nithar Formation are plotted against their sorting values and their correlation coefficient value is computed (0.05) which shows a moderate relationship between the two parameters (Figure 28). The mean size versus roundness plot shows a moderate positive relationship between the two parameters with correlation coefficient value of 0.03. The mean size versus sphericity diagram shows a moderate negative relationship indicating that sphericity of the grains decreases as their size increases. The correlation coefficient value is - 0.45. Plotting of the roundness versus sorting shows negative relationship with correlation coefficient value of 0.23. The plot of sphericity versus sorting shows a

Table 10. Grain size parameters of Nithar Formation Sandstones

Sample No.	**Mz**	**Verbal limit**	**σ I**	**Verbal limit**	**SKi**	**Verbal limit**	**K_G**	**Verbal limit**
N4	2.7	Medium-grained	0.82	Moderately sorted	0.11	Fine skewed	1.72	Very leptokurtic
N6	2.05	Medium-grained	0.73	Moderately sorted	-0.11	Coarse skewed	0.91	Mesokurtic
N9	2.33	Medium-grained	0.57	Moderately well sorted	0.12	Fine skewed	1.17	Leptokurtic
N12	2.53	Medium-grained	0.64	Moderately well sorted	0.09	Near symmetrical	0.79	Platykurtic
N14	2.10	Medium-grained	0.76	Moderately sorted	-0.09	Near symmetrical	0.94	Mesokurtic
N17	2.19	Medium-grained	0.71	Moderately sorted	0.03	Near symmetrical	1.07	Mesokurtic
N19	2.52	Medium-grained	0.78	Moderately sorted	0.08	Near symmetrical	0.81	Platykurtic
N21	2.13	Medium-grained	0.53	Moderately well sorted	0.01	Near symmetrical	0.88	Platykurtic
N22	2.51	Medium-grained	0.40	Moderately well sorted	0.16	Near symmetrical	0.85	Platykurtic
N23	2.27	Medium-grained	0.53	Moderately well sorted	0.17	Near symmetrical	0.87	Platykurtic
Avg.	2.3		0.64		0.57		1.00	

Table 11. Roundness parameters of Nithar Formation Sandstones

Sample No	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
N4	115	--	--	--	--	64	55.6	49	42.6	2	1.7	--	--	0.35
N6	100	--	--	--	--	52	52	47	47	1	1	--	--	0.35
N9	103	--	--	--	--	43	41.7	60	58.2	--	--	--	--	0.46
N12	109	--	--	--	--	51	46.7	58	53.3	--	--	--	--	0.36
N14	122	--	--	--	--	49	40.1	73	59.8	1	0.8	--	--	0.37
N17	118	--	--	--	--	56	47.4	62	52.5	--	--	-	--	0.36
N19	102	--	--	--	--	48	47	54	52.9	3	2.9	--	--	0.38
N21	128	--	--	--	--	55	42.9	73	57	--	--	--	--	0.36
N22	119	--	--	--	--	52	43.6	67	56.3	1	0.8	--	--	0.37
N23	120					58	48.3	62	51.6	1	0.8	--	--	0.36
Avg.							46.5		53.1		1.3			0.37

Table 12. Sphericity parameters of Nithar Formation Sandstones

Sample No	Total grain	High Sphericity		Low Sphericity		Mean Sphericity
		N	%	N	%	
N4	110	23	20.9	87	79.1	0.42
N6	103	35	33.9	68	66.1	0.50
N9	119	31	26	88	74.0	0.45
N12	122	18	14.7	104	85.3	0.38
N14	117	21	17.9	96	82.1	0.40
N17	109	27	24.7	82	75.3	0.44
N19	115	20	17.3	95	82.7	0.40
N21	120	18	15	102	85.0	0.39
N22	105	12	11.4	93	88.6	0.36
N23	112	20	17.8	92	82.2	0.40
Avg.			19.96			0.41

Table 13. Textural maturity parameters of Nithar Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
N4	2.7	Medium	--	0.82	Moderately sorted	0.35	Subangular to subrounded	Submatured
N6	2.05	Medium	--	0.73	Moderately sorted	0.35	Subangular to subrounded	Submatured
N9	2.33	Medium	--	0.57	Moderately well sorted	0.46	Subrounded	Submatured
N12	2.53	Medium	--	0.64	Moderately well sorted	0.36	Subrounded	Submatured
N14	2.10	Medium	--	0.76	Moderately sorted	0.37	Subrounded	Submatured
N17	2.19	Medium	--	0.71	Moderately sorted	0.36	Subrounded	Submatured
N19	2.52	Medium	--	0.78	Moderately sorted	0.38	Subrounded	Submatured
N21	2.13	Medium	--	0.53	Moderately well sorted	0.36	Subrounded	Submatured
N22	2.51	Medium	--	0.40	Moderately well sorted	0.37	Subrounded	Submatured
N23	2.27	Medium	--	0.53	Moderately well sorted	0.36	Subrounded	Submatured

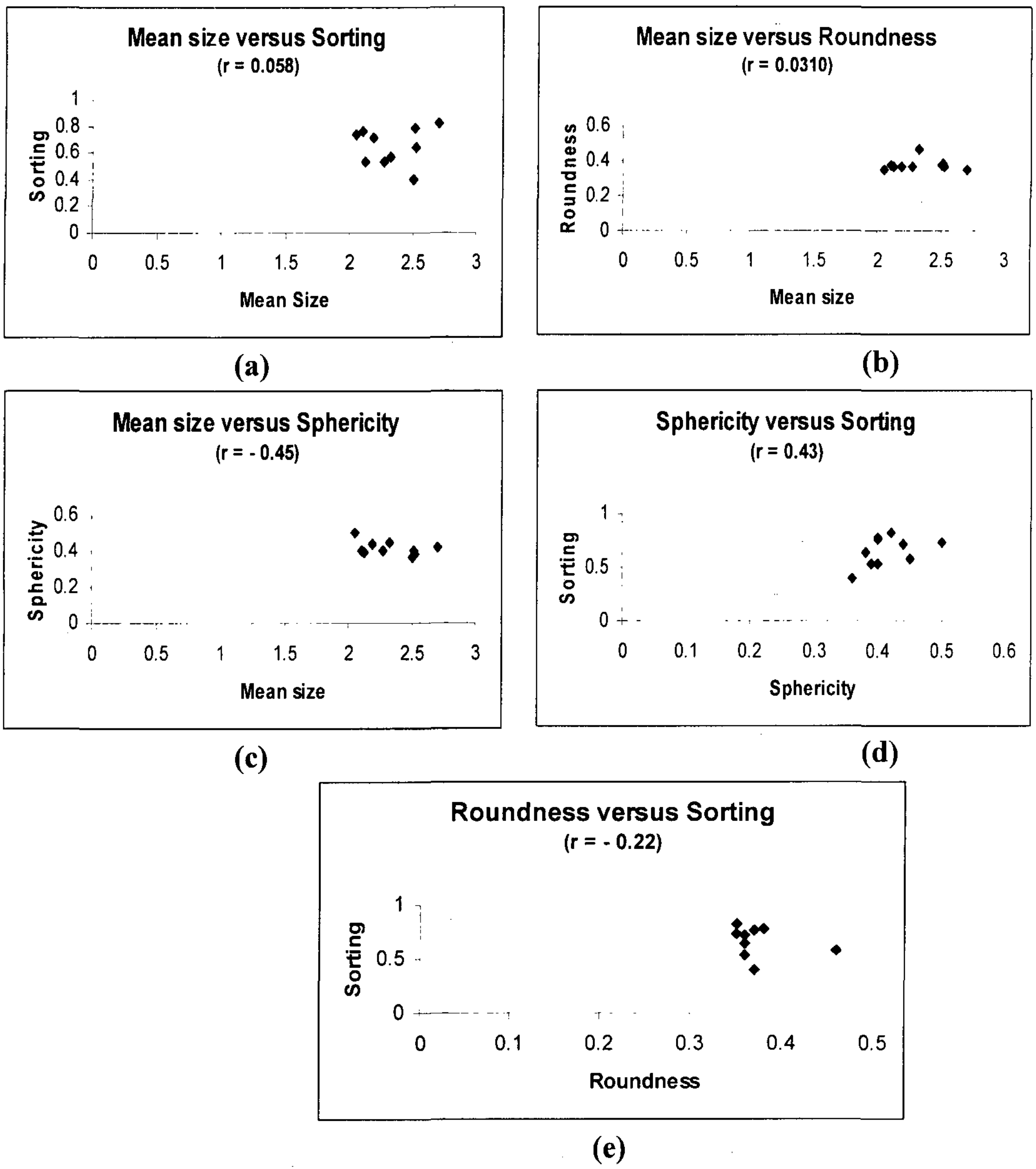


Figure 28. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Nithar Formation, Bayana Basin.

positive relationship with correlation coefficient of 1. Thus as the sphericity increases, sorting also increases.

Interpretation: Textural study of 10 samples of sandstones of Nithar Formation shows that sandstones are medium-grained, moderately well sorted, near symmetrical and mostly platykurtic. Majority of the grains show low sphericity and are subangular to subrounded. Bivarient plot of various parameters indicates that mean size versus sorting and mean size versus roundness has poor but positive relationship. Mean size versus sphericity and roundness versus sorting have inversely moderate relationship whereas sphericity versus sorting has a very good positive relationship. Overall texture of the sandstone can be considered as sub-mature.

HATHORI SANDSTONES
(Jahaj-Govindpura Volcanic Formation)

The graphic mean size (**Mz**) of the sandstones of Jahaj-Govindpura volcanic (JGV) Formation range from 2.05 Φ to 3.95 Φ, average 2.2 Φ, indicating medium grains. **σ I** values of the JGV sandstones range from 0.48 Φ to 1.29 Φ indicating poorly sorted to well sorted. Most of the grains are moderately sorted to moderately well sorted, average is 0.64 Φ. **Ski** ranges from – 0.01 to + 0.27, average being 0.18. Most of the samples fall into the category of near symmetrical followed by coarse skewed to fine skewed. **K_G** values of the sandstones of JGV Formation range from 0.84 to 1.53, average is 1.08 indicating variation from mesokurtic to leptokurtic, followed by platykurtic (Table 14). 50.95% of the grain studied showed low sphericity while 49.05% is of high sphericity (Table 15). The mean sphericity values of the individual samples range from 0.55 to 0.64, average 0.59. Roundness of the JGV sandstones ranges widely from very angular to well rounded (Table 16). But mostly, the grains are subangular (average 37.2%) to subrounded (average 40.8%). The mean roundness values range from 0.35 to 0.46, average being 0.37.

The studied sandstones are sub-mature as most of the grains are subangular to subrounded (Table 17). Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of JGV Formation were plotted against their sorting values and their correlation coefficient value was computed (- 0.03) which shows a poor and inverse relationship (Figure 29). . While the mean size versus roundness plot shows a moderate but inverse relationship between the two parameters with correlation coefficient value of 0.31, the mean size versus sphericity diagram shows a moderate inverse relationship indicating that sphericity of the grains decreases as their size increases. The correlation coefficient value is -0.2. Plotting of roundness versus sorting show poor but positive relationship with correlation coefficient value of 0.04. The plot of sphericity versus sorting shows a good and positive relationship with correlation coefficient of 0.50. It means, as sphericity increases, sorting also increases.

Interpretation: Textural study of 19 samples of tuffacious sandstones of JGV Formation shows that sandstones are medium-grained followed by fine-grained, poorly sorted to well sorted , near symmetrical to coarse skewed and kurtosis ranges from platykurtic to mesokurtic, followed by leptokurtic and very leptokurtic. Low spherical grains dominate and grains are angular to well-rounded. Bivarient plotting of different parameters show that mean size versus sorting and roundness versus sorting has poor relationship. Mean size versus roundness and mean size versus sphericity have moderate relationship whereas sphericity versus sorting has a very good positive relationship. Based on it, textural attributes of the sandstones of JGV Formation can be considered as sub-mature.

Table 14. Grain size parameters of JGV Formation Sandstones

Sample No.	**Mz**	**Verbal limit**	**σ I**	**Verbal limit**	**SKi**	**Verbal limit**	**K_G**	**Verbal limit**
V1	2.7	Medium-grained	0.64	Moderately well sorted	-0.033	Coarse skewed	1.012	Mesokurtic
V3	3.95	Fine-grained	0.80	Moderately sorted	-0.01	Near symmetrical	1.08	Mesokurtic
V5	3.28	Fine-grained	0.73	Moderately sorted	0.009	Near symmetrical	1.04	Mesokurtic
V7	2.56	Medium-grained	0.58	Moderately well sorted	-0.003	Near symmetrical	1.06	Mesokurtic
V9	2.61	Medium-grained	0.58	Moderately Well sorted	-0.238	Coarse skewed	1.22	Laptokurtic
V11	2.58	Medium-grained	0.48	Well sorted	-0.223	Coarse skewed	0.87	Mesokurtic
V12	2.78	Medium-grained	0.63	Moderately well sorted	-2.671	Coarse skewed	1.03	Mesokurtic
V14	2.28	Medium-grained	1.29	Poorly sorted	-0.12	Coarse skewed	0.92	Mesokurtic
V15	2.68	Medium-grained	0.60	Moderately well sorted	-0.045	Near symmetrical	1.20	Laptokurtic
V17	2.98	Medium-grained	1.02	Poorly sorted	0.11	Near symmetrical	1.41	Laptokurtic
V19	2.53	Medium-grained	0.50	Moderately well sorted	0.093	Near symmetrical	0.84	Mesokurtic
V21	2.66	Medium-grained	0.76	Moderately sorted	-0.03	Near symmetrical	1.53	Very Laptokurtic
V23	2.83	Medium-grained	0.66	Moderately well sorted	-0.01	Near symmetrical	0.95	Mesokurtic
V25	2.35	Medium-grained	0.57	Moderately well sorted	-0.19	Near symmetrical	1.32	Laptokurtic
V27	2.05	Medium-grained	0.93	Moderately sorted	.02	Near symmetrical	0.87	Platykurtic
V29	2.5	Medium-grained	0.60	Moderately well sorted	-0.075	Near symmetrical	1.49	Laptokurtic
V31	2.62	Medium-grained	0.90	Moderately sorted	0.27	Fine skewed	0.95	Mesokurtic
V32	2.45	Medium-grained	0.56	Moderately well sorted	-0.176	Near symmetrical	0.92	Mesokurtic
V33	2.51	Medium-grained	1.02	Poorly sorted	-0.15	Coarse skewed	0.84	Platykurtic
Avg.	2.2		0.64		-0.18		1.08	

Table 15. Sphericity parameters of JGV Formation Sandstones

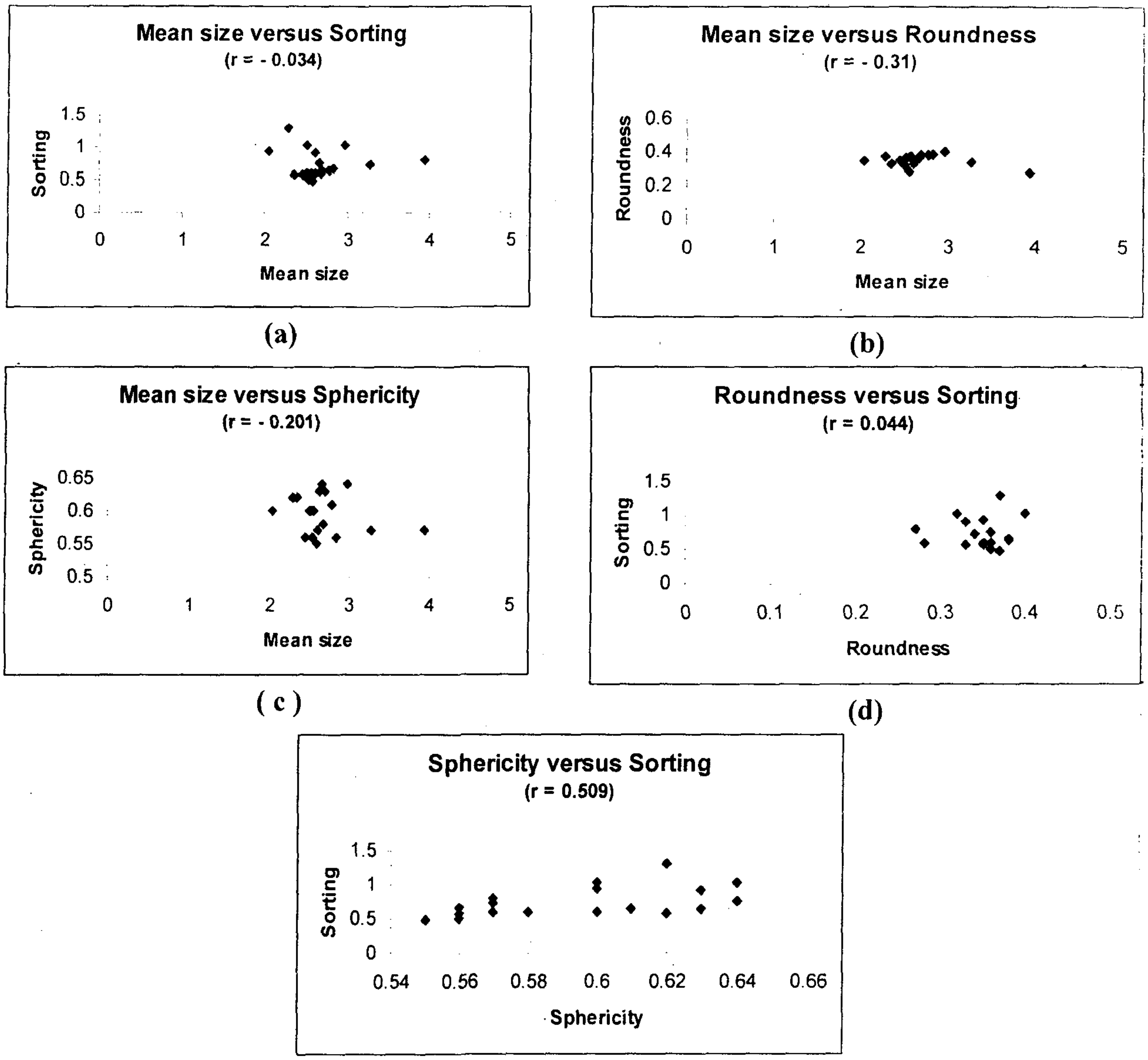
Sample No	Total grain	High Sphericity		Low Sphericity		Mean Sphericity
		N	%	N	%	
V1	100	56	56	44	44	0.63
V3	100	46	46	54	54	0.57
V5	100	45	45	55	55	0.57
V7	100	51	51	49	49	0.60
V9	100	45	45	55	55	0.57
V11	100	43	43	57	57	0.55
V12	122	64	52	58	48	0.61
V14	103	55	53	48	47	0.62
V15	80	38	48	42	52	0.58
V17	100	57	57	43	43	0.64
V19	101	45	44	56	55	0.56
V21	104	60	44	44	56	0.64
V23	97	43	44	54	55	0.56
V25	105	56	53	49	47	0.62
V27	110	55	50	55	50	0.6
V29	80	40	50	40	50	0.6
V31	107	59	55	48	45	0.63
V32	85	38	45	47	55	0.56
V33	100	51	51	49	49	0.60
Avg			49.05		50.95	0.59

Table 16. Roundness parameters of JGV Formation Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
V1	95	--	--	10	10	36	38	37	39	9	9	3	3	0.38
V3	100	--	--	26	26	22	22	25	25	6	6	2	2	0.27
V5	107	--	--	31	29	34	32	34	32	5	5	3	3	0.34
V7	100	--	--	20	20	25	25	28	28	5	5	3	3	0.28
V9	90	--	--	14	15	36	40	35	39	4	4	1	1	0.35
V11	103	--	--	10	9	39	38	45	44	5	4	4	4	0.37
V12	106	--	--	8	7	33	31	54	51	11	10	--	--	0.38
V14	90	--	--	15	17	30	33	40	44	3	3	2	2	0.37
V15	62	--	--	1	1	29	47	29	47	2	3	1	1	0.36
V17	90	--	--	5	6	35	39	45	50	3	3	1	1	0.40
V19	112	--	--	6	5	54	48	53	47	8	7	1	1	0.36
V21	100	--	--	12	12	30	30	53	53	5	5	--	--	0.36
V23	109	--	--	8	7	45	41	52	48	3	3	1	1	0.38
V25	120	--	--	11	9	45	38	51	43	10	8	2	2	0.33
V27	102	--	--	25	25	35	34	39	38	1	1	3	3	0.35
V29	105	--	--	3	3	59	56	37	35	5	5	1	1	0.35
V31	100	--	--	25	25	35	35	36	36	3	3	1	1	0.33
V32	108	--	--	7	6	50	46	47	44	4	4	--	--	0.35
V33	98	--	--	30	31	33	34	33	34	1	1	1	1	0.32
Avg					13.8		37.2		40.8		4.6		1.5	0.35

Table 17. Textural maturity parameters of JGV formation sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
V1	2.7	Medium-grained	--	0.64	Moderately well sorted	0.38	Subrounded	Submatured
V3	3.95	Fine-grained	--	0.80	Moderately sorted	0.27	Subangular	Submatured
V5	3.28	Fine-grained	--	0.73	Moderately sorted	0.34	Subangular	Submatured
V7	2.56	Medium-grained	--	0.58	Moderately well sorted	0.28	Subangular	Submatured
V9	2.61	Medium-grained	--	0.58	Moderately well sorted	0.35	Subrounded to subangular	Submatured
V11	2.58	Medium-grained	--	0.48	Well sorted	0.37	Subrounded	Submatured
V12	2.78	Medium-grained	--	0.63	Moderately well sorted	0.38	Subrounded	Submatured
V14	2.28	Medium-grained	--	1.29	Poorly sorted	0.37	Subrounded	Submatured
V15	2.68	Medium-grained	--	0.60	Moderately well sorted	0.36	Subrounded	Submatured
V17	2.98	Medium-grained	--	1.02	Poorly sorted	0.40	Subrounded	Submatured
V19	2.53	Medium-grained	--	0.50	Moderately well sorted	0.36	Subrounded	Submatured
V21	2.66	Medium-grained	--	0.76	Moderately sorted	0.36	Subrounded	Submatured
V23	2.83	Medium-grained	--	0.66	Moderately well sorted	0.38	Subrounded	Submatured
V25	2.35	Medium-grained	--	0.57	Moderately well sorted	0.33	Subangular	Submatured
V27	2.05	Medium-grained	--	0.93	Moderately sorted	0.35	Subrounded to subangular	Submatured
V29	2.5	Medium-grained	--	0.60	Moderately well sorted	0.35	Subrounded to subangular	Submatured
V31	2.62	Medium-grained	--	0.90	Moderately sorted	0.33	subangular	Submatured
V32	2.45	Medium-grained	--	0.56	Moderately well sorted	0.35	Subrounded to subangular	Submatured
V33	2.51	Medium-grained	--	1.02	Poorly sorted	0.32	Subangular	Submatured



(e)

Figure 29. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Jahaj-Govindpura Volcanic Formation, Bayana Basin.

SITAKUND SANDSTONES
(Jogipura Formation)

The Mz values of the sandstones of Jogipura Formation range from 1.3 Φ to 3.95 Φ, average 2.4 Φ, indicating medium grains. The sorting values of Jogipura sandstones range from 0.43 Φ to 0.92 Φ indicating moderately sorted to moderately well sorted, average is 0.72 Φ suggesting moderately sorted texture. **Ski** values ranges from – 0.01 to + 0.214, average being - 0.14. The samples vary from fine skewed to strongly coarse skewed. The $\mathbf{K_G}$ values of the sandstones of Jogipura Formation range from 0.80 to 1.18, average being 0.95 indicating variation from mesokurtic to leptokurtic, followed by platykurtic (Table 18). 56.48% of the grain studied shows low sphericity while 43.5% is of high sphericity. The mean sphericity values of the individual samples range from 0.49 to 0.60, average 0.55 (Table 19). The sandstones have grain roundness ranging from very angular to well rounded. But in most of the samples, majority of the grains are subrounded (avg. 43.6 %) to subangular (average 38.7 %) (Table 20). The mean roundness values range from 0.34 to 0.42, average being 0.36. The studied sandstones are sub-matured as most of the grains are subangular to subrounded (Table 21). Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Jogipura Formation were plotted against their sorting values and their correlation coefficient value was computed (-0.11) which shows a moderate inverse relationship (Figure 30). The mean size versus roundness plot shows a moderate but inverse relationship between the two parameters with correlation coefficient value of - 0.22. The mean size versus sphericity diagram shows a moderate positive relationship. The correlation coefficient value is 0.16. Plotting of roundness versus sorting parameters shows moderate but positive relationship with correlation coefficient value of 0.198. The plot of sphericity versus sorting shows a moderate and positive relationship with correlation coefficient of 0.25.

Table 18. Grain size parameters of Jogipura Formation Sandstones

Sample No.	Mz	Verbal limit	σ 1	Verbal limit	SKi	Verbal limit	K_G	Verbal limit
S2	3.31	Fine-grained	0.71	Moderately well sorted	- 0.23	Near symmetrical	0.82	Platykurtic
S3	3.11	Fine-grained	0.62	Moderately well sorted	-0.557	Strongly coarse skewed	0.901	Mesokurtic
S4	1.3	Fine-grained	0.74	Moderately sorted	0.193	Fine skewed	0.80	Platykurtic
S5	3.12	Fine-grained	0.43	Well sorted	0.070	Near symmetrical	1.095	Mesokurtic
S8	1.35	Medium-grained	0.71	Moderately Well sorted	0.17	Near symmetrical	0.80	Platykurtic
S10	2.41	Medium-grained	0.80	Moderately well sorted	-0.62	Coarse skewed	0.74	Platykurtic
S12	2.80	Medium-grained	0.75	Moderately sorted	-0.08	Near symmetrical	1.10	Mesokurtic
S14	2.58	Medium-grained	0.69	Moderately well sorted	-0.38	Strongly coarse skewed	1.18	Laptokurtic
S16	2.88	Medium-grained	0.87	Moderately sorted	-0.12	Near symmetrical	1.05	Mesokurtic
S18	2.68	Medium-grained	0.92	Moderately sorted	0.02	Near symmetrical	1.04	Mesokurtic
S20	3.3	Fine-grained	0.64	Moderately well sorted	0.21	Strongly coarse skewed	0.88	Platykurtic
S22	3.95	Fine-grained	0.80	Moderately sorted	-0.01	Near symmetrical	1.08	Mesokurtic
Avg.	2.4		0.72		-1.45		0.95	

Table 19. Sphericity parameters of Jogipura Formation Sandstones

Sample No.	**Total grain**	**High Sphericity**		**Low Sphericity**		**Mean Sphericity**
		N	%	N	%	
S2	140	60	42.8	80	57.2	0.55
S3	110	45	40.9	65	59.1	0.54
S4	115	45	39.1	56	60.9	0.49
S5	125	55	44	70	56	0.56
S8	110	52	47.2	58	52.8	0.58
S10	130	60	46.1	70	53.9	0.57
S12	100	40	40	60	60	0.54
S14	110	47	42.7	63	57.3	0.55
S16	105	46	43.8	59	56.2	0.56
S18	112	57	50.8	55	49.2	0.60
S20	117	49	41.8	68	58.2	0.55
S22	123	53	43.0	70	57	0.55
Avg			43.5		56.48	0.55

Table 20. Roundness parameters of Jogipura Formation Sandstones

Sample No.	**Total grain**	**Very angular**		**Angular**		**Subangular**		**Subrounded**		**Rounded**		**Well Rounded**		**Mean roundness**
		N	%	N	%	N	%	N	%	N	%	N	%	
S2	120	4	3.3	16	13.3	44	36.6	46	38.3	8	6.6	2	1.6	0.35
S3	122	3	2.4	17	13.9	43	35.2	55	45	4	3.2	--	--	0.34
S4	110	1	0.90	10	9.0	50	45.4	48	43.6	--	--	--	--	0.34
S5	100	--	--	5	5	45	45	45	45	5	5	--	--	0.36
S8	110	--	--	5	4.5	30	27.2	50	45.4	20	18.1	5	4.5	0.42
S10	120	2	1.6	10	8.3	45	37.5	48	40	10	8.3	5	4.1	0.40
S12	95	--	--	3	3.1	43	45.2	43	45.2	4	4.2	2	2.1	0.37
S14	100	--	--	5	5	45	45	45	45	5	5	--	--	0.36
S16	105	2	1.9	10	9.52	40	38.0	46	43.8	6	5.7	--	--	0.35
S18	109	3	2.7	5	4.5	40	36.6	48	44	10	9.1	3	2.7	0.38
S20	100	1	1	7	7	39	39	40	40	12	12	1	1	0.38
S22	118	--	--	10	8.4	40	33.8	57	48.3	9	7.6	2	1.6	0.38
Avg			1.91		7.6		38.7		43.6		7.7		2.5	0.36

Table 21. Textural maturity parameters of Jogipura sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
S2	3.31	Fine-grained	--	0.71	Moderately well sorted	0.35	Subrounded to subangular	Submatured
S3	3.11	Fine-grained	--	0.62	Moderately well sorted	0.34	Subangular	Submatured
S4	1.3	Fine-grained	--	0.74	Moderately sorted	0.34	Subangular	Submatured
S5	3.12	Fine-grained	--	0.43	Well sorted	0.36	Subrounded	Submatured
S8	1.35	Medium-grained	--	0.71	Moderately well sorted	0.42	Subrounded	Submatured
S10	2.41	Medium-grained	--	0.80	Moderately well sorted	0.40	Subrounded	Submatured
S12	2.80	Medium-grained	--	0.75	Moderately sorted	0.37	Subrounded	Submatured
S14	2.58	Medium-grained	--	0.69	Moderately well sorted	0.36	Subrounded	Submatured
S16	2.88	Medium-grained	--	0.87	Moderately sorted	0.35	Subangular	Submatured
S18	2.68	Medium-grained	--	0.92	Moderately sorted	0.38	Subrounded	Submatured
S20	3.3	Fine-grained	--	0.64	Moderately well sorted	0.38	Subrounded	Submatured
S22	3.95	Fine-grained	--	0.80	Moderately sorted	0.38	Subrounded	Submatured

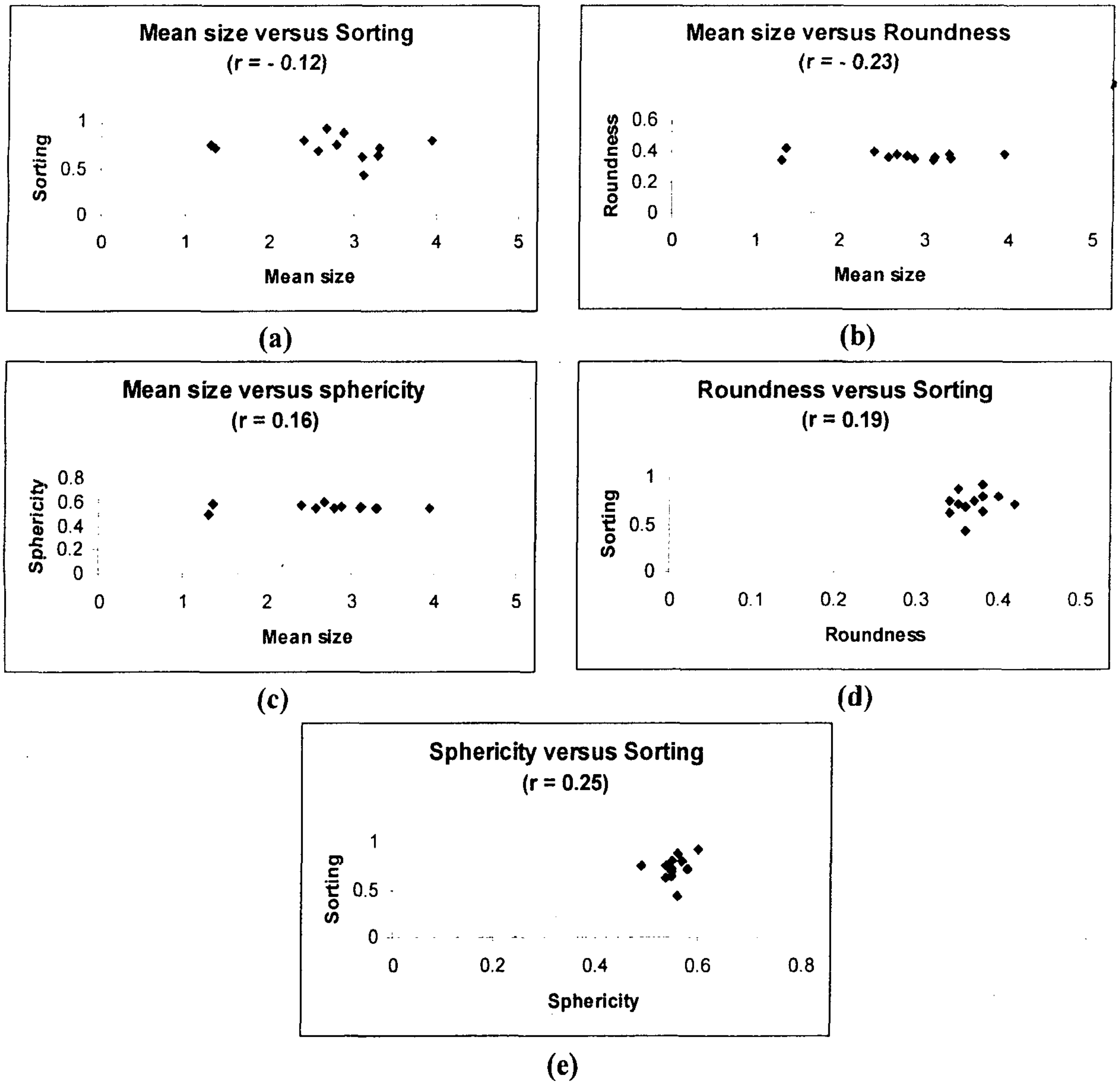


Figure 30. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Jogipura Formation, Bayana Basin.

Interpretation: Twelve samples of sandstones, collected from the Sitakund locality of Jogipura Formation, are fine to medium-grained, moderately well sorted, fine skewed to strongly coarse skewed and varies from mesokurtic to leptokurtic, followed by platykurtic. Most of the grains are subangular to subrounded and of low sphericity. Bivarient plotting of mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting show moderate relationship between them. Thus the sandstone can be assigned as texturally sub-mature.

BHAGRAIN SANDSTONES
(Badalgarh Formation)

The Mz values range from 1.63 Φ to 2.2 Φ, average 1.78 Φ, indicating medium grain (Table 22). Sorting ranges from 0.43 Φ to 0.63 Φ with an average value of 0.51 Φ indicating moderately well sorted nature. **Ski** values ranges from – 0.03 to - 1.75, average being - 0.38. The samples vary from near symmetrical to coarse skewed. K_G values of the sandstones of Bhagrain of Badalgarh Formation range from 0.91 to 1.12, average being 0.97 indicating variation from mesokurtic to leptokurtic. Most of the grain studied showed low sphericity occupying 64.4% while 35.5% is of high sphericity (Table 23). The mean sphericity values of the individual samples range from 0.47 to 0.60, average 0.55, average being 0.50. The sandstones have grain roundness ranging from very angular to well rounded (Table 24). But in most of the samples, majority of the grains are subrounded (average 48.9 %) to subangular (average 44.8 %). The mean roundness values range from 0.28 to 0.36, average being 0.34. The studied sandstones are sub-mature as most of the grains are subangular to subrounded (Table 25). Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Bhagrain were plotted against their sorting values and their correlation coefficient value was computed (0.36) which shows a

Table 22. Grain size parameters of Bhagrain Sandstones of Badalgarh Formation

Sample No.	**Mz**	**Verbal limit**	**σ 1**	**Verbal limit**	**SKi**	**Verbal limit**	**K_G**	**Verbal limit**
Bg1	1.65	Medium-grained	0.63	Moderately well sorted	- 031	Coarse skewed	1.01	Leptokurtic
Bg2	1.63	Medium-grained	0.50	Moderately well sorted	- 1.75	Coarse skewed	0.93	Mesokurtic
Bg3	2.2	Medium-grained	0.45	Moderately well sorted	- 0.03	Near symmetrical	0.94	Mesokurtic
Bg5	1.71	Medium-grained	0.43	Moderately well sorted	- 0.10	Coarse skewed	0.91	Mesokurtic
Bg7	1.66	Medium-grained	0.50	Moderately well sorted	- 0.13	Coarse skewed	0.93	Mesokurtic
Bg9	1.83	Medium-grained	0.57	Moderately well sorted	- 0.13	Coarse skewed	1.12	Leptokurtic
Avg.	1.78		0.51		- 0.38		0.97	

Table 23. Sphericity parameters of Bhagrain Sandstones

Sample No	**Total grain**	**High Sphericity**		**Low Sphericity**		**Mean Sphericity**
		N	%	N	%	
Bg1	110	38	34.5	72	65.5	0.50
Bg2	120	35	29.1	85	70.9	0.47
Bg3	105	38	36.1	67	36.9	0.51
Bg5	117	42	35.8	75	64.2	0.51
Bg7	100	36	36	64	64	0.51
Bg9	115	48	41.7	67	58.3	0.55
Avg.			35.5		64.4	0.50

Table 24. Roundness parameters of Bhagrain Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean Roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
Bg1	100	-	-	3	3	48	48	47	47	2	2	--	--	0.35
Bg2	115	-	-	1	0.86	53	46	58	50	3	2.6	--	--	0.36
Bg3	120	-	-	-	-	54	45	60	50	5	4.1	1	0.8	0.28
Bg5	98	1	1.0	4	4	44	44.8	45	45.9	3	3	1	1	0.36
Bg7	118	-	-	8	6.7	50	42.3	58	49.1	2	1.6	--	--	0.35
Bg9	110	-	-	4	3.6	47	42.7	57	51.8	2	1.8	--	--	0.36

Table 25: Textural maturity parameters of Bhgarain Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
Bg1	1.65	Medium-grained	--	0.63	Moderately well sorted	0.35	Subrounded to subangular	Submatured
Bg2	1.63	Medium-grained	--	0.50	Moderately well sorted	0.36	Subrounded	Submatured
Bg3	2.2	Medium-grained	--	0.45	Moderately well sorted	0.28	Subangular	Submatured
Bg5	1.71	Medium-grained	--	0.43	Moderately well sorted	0.36	Subrounded	Submatured
Bg7	1.66	Medium-grained	--	0.50	Moderately well sorted	0.35	Subrounded to subangular	Submatured
Bg9	1.83	Medium-grained	--	0.57	Moderately well sorted	0.36	Subrounded	Submatured

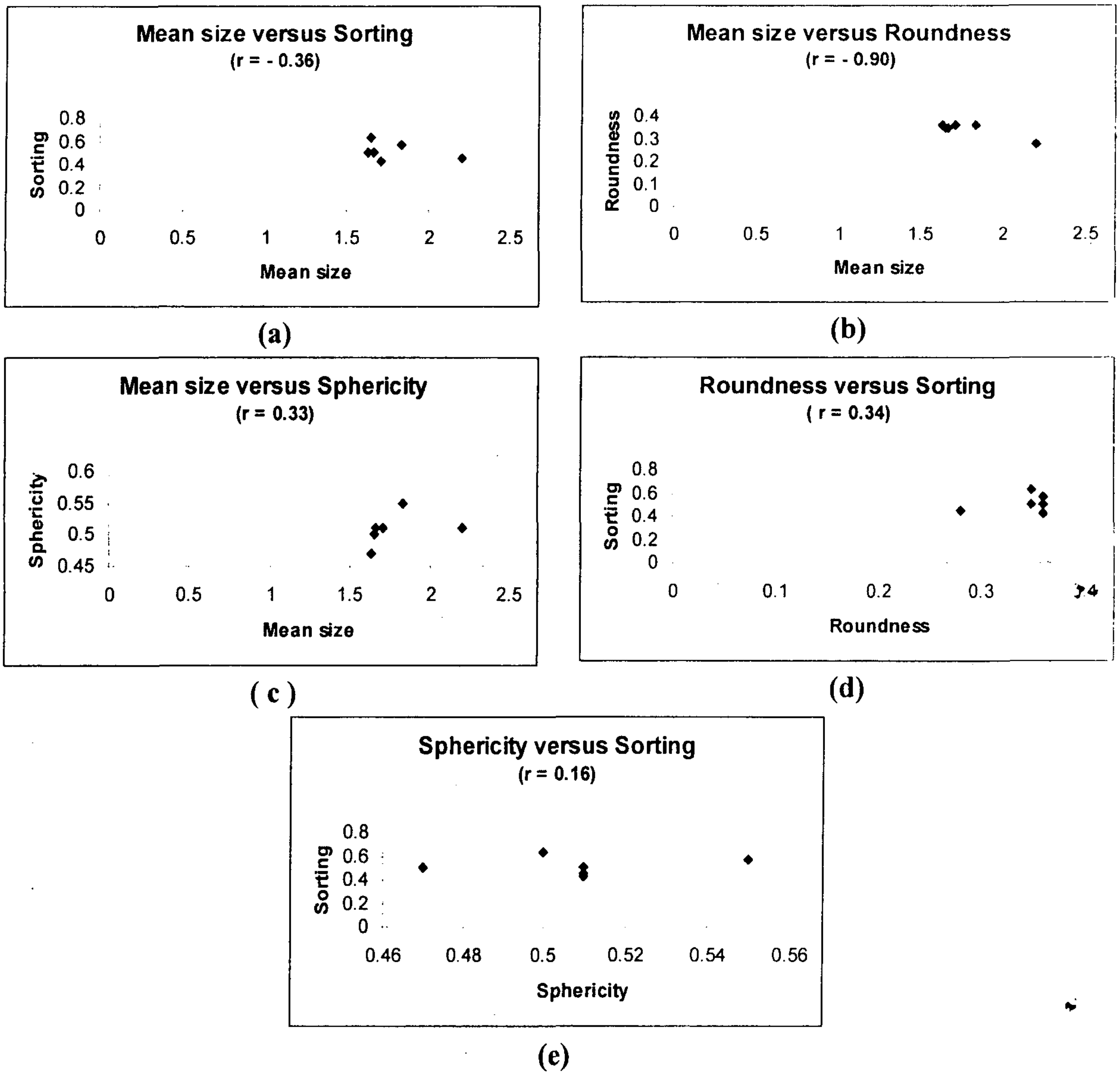


Figure 31. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Bhagrain, Badalgarh Formation, Bayana Basin.

moderate inverse relationship (Figure 31). . The mean size versus roundness plot shows a moderate but inverse relationship between the two parameters with correlation coefficient value of -0.90. The mean size versus sphericity diagram shows a moderate positive relationship. The correlation coefficient value is 0.33. Roundness versus sorting plot shows moderate but positive relationship with correlation coefficient value of 0.34. and the plot of sphericity versus sorting shows a moderate and positive relationship with correlation coefficient of 0.16.

ALAPURI SANDSTONES
(Badalgarh Formation)

The values of the **Mz** of sandstones of Alapuri locality range from 0.87 Φ to 3.95 Φ, average 2.39 Φ, indicating variation from fine-grained to coarse-grained nature. The **σ I** values range from 0.64 Φ to 1.03 Φ indicating poorly sorted to moderately well sorted nature (Table 26). Average is 0.51 Φ. **Ski** values ranges from – 0.01 to 0.10, average being - 0.05. The samples vary from near symmetrical to coarse skewed. The values of $\mathbf{K_G}$ of the Alapuri sandstones range from 0.81 to 1.72, average being 1.12 indicating variation from mesokurtic to leptokurtic followed by platykurtic.

The sandstones have grain roundness ranging from angular to well-rounded. Majority of the grains are subrounded (average 46.5%) to subangular (average 38.1%) (Table 27). The mean roundness of the individual samples range from 0.35 to 0.39, average being 0.35. Most of the grains studied show low sphericity (72%) and 28% is of high sphericity (Table 28). The mean sphericity values of the individual samples range from 0.43 to 0.49, average 0.46. The studied sandstones are sub-mature as most of the grains are subangular to subrounded (Table 29). Absence of clay indicates that the sandstones were deposited under high energy environment.

Table 26. Grain size parameters of Alapuri Sandstones of Badalgarh Formation

Sample No.	Mz	Verbal limit	σ 1	Verbal limit	SKi	Verbal limit	K_G	Verbal limit
A1	3.92	Fine-grained	0.81	Moderately sorted	- 0.01	Near symmetrical	1.07	Mesokurtic
A2	3.33	Fine-grained	0.64	Moderately well sorted	- 0.21	Strongly coarse skewed	0.88	Platykurtic
A4	0.93	Coarse-grained	1.02	Poorly sorted	0.02	Near symmetrical	0.90	Mesokurtic
A6	3.95	Fine-grained	0.80	Moderately sorted	- 0.01	Near symmetrical	1.06	Mesokurtic
A8	0.87	Coarse-grained	1.01	Poorly sorted	- 0.13	Coarse skewed	0.81	Platykurtic
A9	2.76	Medium-grained	0.88	Moderately sorted	0.10	Fine skewed	1.72	Very Leptokurtic
A11.	0.98	Coarse-grained	1.03	Poorly sorted	- 0.11	Coarse skewed	1.43	Leptokurtic
Avg.	2.39		0.88		0.05		1.12	

Table 27. Roundness parameters of Alapuri Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean Roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
A1	115	-	-	11	9.5	50	43.5	51	44.3	3	2.6	--	--	0.35
A2	120	-	-	12	10	49	40.8	54	45	4	3.3	1	0.8	0.35
A4	103	-	-	9	8.7	40	38.8	51	49.5	3	2.9			0.36
A6	100	-	-	15	15	30	30	37	37	15	15	3	3	0.39
A8	123	-	-	17	13.8	42	34.1	50.4	50.4	2	1.6	--	--	0.35
A9	118	-	-	8	6.7	50	42.3	49.1	49.1	2	1.6	--	--	0.35
A11	107			10	9.3	40	37.3	50.4	50.4	2	1.8	1	0.9	0.36
Avg					10.4		38.1		46.5		4.1		0.67	0.35

Table 28. Sphericity parameters of Alapuri Sandstones

Sample No	**Total grain**	**High Sphericity**		**Low Sphericity**		**Mean Sphericity**
		N	%	N	%	
A1	115	37	32.1	78	67.9	0.49
A2	100	32	32	68	68	0.49
A4	120	30	25	90	75	0.45
A6	110	35	31.8	75	68.2	0.49
A8	122	27	22.1	95	77.9	0.43
A9	118	33	27.9	85	74.8	0.46
A11	115	29	25.2	86	72	0.45
Avg			28			0.46

Table 29. Textural maturity parameters of Alapuri Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
A1	3.92	Fine-grained	--	0.81	Moderately sorted	0.35	Subrounded to subangular	Submatured
A2	3.33	Fine-grained	--	0.64	Moderately well sorted	0.35	Subrounded to subangular	Submatured
A4	0.93	Coarse-grained	--	1.02	Poorly sorted	0.36	Subrounded	Submatured
A6	3.95	Fine-grained	--	0.80	Moderately sorted	0.39	Subrounded	Submatured
A8	0.87	Coarse-grained	--	1.01	Poorly sorted	0.35	Subrounded to subangular	Submatured
A9	2.76	Medium-grained	--	0.88	Moderately sorted	0.35	Subrounded to subangular	Submatured
A11	0.98	Coarse-grained		1.03	Poorly sorted	0.36	Subrounded	Submatured

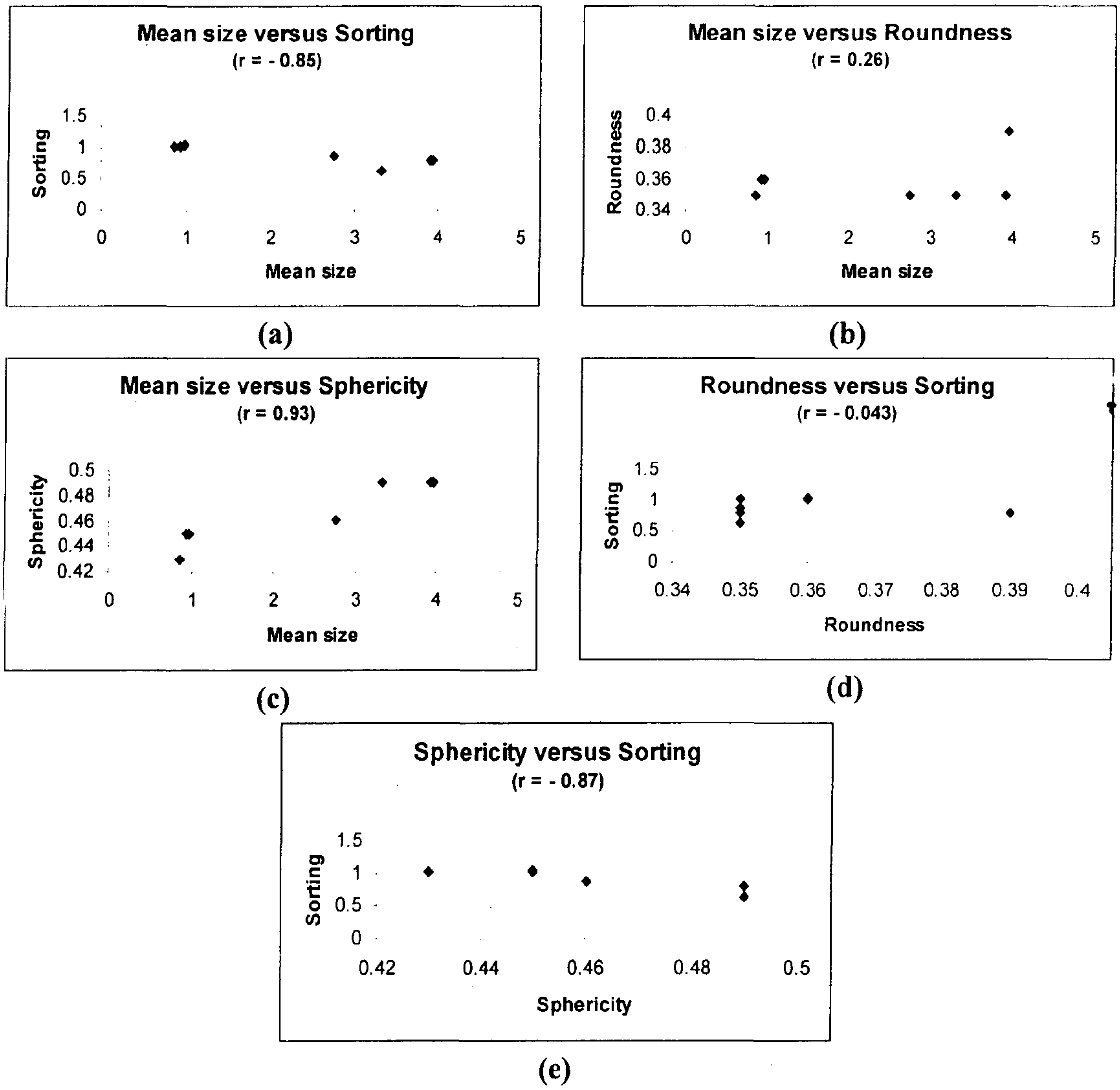


Figure 32. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Alapuri of Badalgarh Formation, Bayana Basin.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Alapuri were plotted against their sorting values and their correlation coefficient value was computed (- 0.85) which shows a moderate inverse relationship (Figure 32). . The mean size versus roundness plot shows a moderate and positive relationship between the two parameters with correlation coefficient value of - 0.26. The mean size versus sphericity diagram shows a good and positive relationship. The correlation coefficient value is 0.93. While roundness versus sorting plot shows poor and inverse relationship with correlation coefficient value of - 0.04. The plot of sphericity versus sorting shows a moderate and inverse relationship with correlation coefficient of - 0.87.

Interpretation: The studied six samples of Bhagrain and seven samples of Alapuri localities of Badalgarh Formation showed that grain size of the sandstones range from fine-grained to medium-grained followed by coarse-grained. Most are poorly sorted to moderately well sorted with near symmetrical to coarse skewness. Most of the samples are mesokurtic followed by leptokurtic to platykurtic. Mostly grains are subangular to subrounded and have low sphericity. Bivarient plotting of different parameters shows poor to moderate relationship among them. Thus Badalgarh Sandstones can be considered as texturally sub-mature.

BAYANA SANDSTONES
(Bayana Formation)

The Mz value of the Bayana Sandstones range from 1.13 Φ to 2.39 Φ, average 1.55 Φ, indicating medium grain nature (Table 30). **σ I** values range from 0.48 Φ to 0.77 Φ, average is 0.64 Φ indicating moderately well sorted to well sorted nature. **Ski** values of the sandstones of the Bayana Formation ranges from – 0.01 to 0.29, average being 0.04. The samples vary from near symmetrical to fine skewed. The **K_G** values of Bayana sandstones range from 0.82 to 1.48, average being 1.02 indicating variation from mesokurtic to leptokurtic followed by platykurtic. The sandstones have grain roundness ranging from very angular to well-rounded. Majority of the grains are subrounded (avg. 35.3 %) to subangular (avg. 35.7 %). The mean roundness of the individual samples range from 0.26 to 0.39, average being 0.33 (Table 31). Most of the studied grains showed low sphericity (66.13 %) and 33.8% is of high sphericity (Table 32). The mean sphericity values of the individual samples range from 0.43 to 0.55, with an average of 0.49. The studied sandstones are sub-mature as most of the grains are subangular to subrounded (Table 33). Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Bayana were plotted against their sorting values and their correlation coefficient value was computed (- 0.01), a poor inverse relationship between the two variables (Figure 33) is observed. The mean size versus roundness plots shows a good and positive relationship between the two parameters with correlation coefficient value of - 0.51. The mean size versus sphericity diagram shows a poor but inverse relationship, the correlation coefficient value being 0.03. Plotting of roundness versus sorting shows poor and inverse relationship with correlation coefficient value of - 0.01. The plot of sphericity versus sorting shows a poor and positive relationship with correlation coefficient of - 0.03.

BHIMNAGAR SANDSTONES
(Bayana Formation)

The mean size of the Bhimnagar Sandstones ranges from 1.31 Φ to 2.31 Φ, average 1.68 Φ, indicating medium-grained texture. The **σ I** values range from 0.48 Φ to 0.93 Φ indicating moderately well sorted to well sorted nature. Average is 0.70 Φ. **Ski** ranges from – 0.013 to 0.29 (Table 34). Average is 0.019 indicating variation from coarse skewed to near symmetrical to fine skewed. The $\mathbf{K_G}$ values of Bayana sandstones range from 0.72 to 1.48, average being 0.93 indicating variation from mesokurtic to leptokurtic followed by platykurtic. The sandstones have grain

Table 30. Grain size parameters of Bayana Sandstones

Sample No.	Mz	Verbal limit	σ 1	Verbal limit	SKi	Verbal limit	Kg	Verbal limit
B5	2.01	Medium-grained	0.48	Well sorted	- 0.13	Near symmetrical	0.98	Mesokurtic
B8	1.16	Medium-grained	0.65	Moderately well sorted	- 0.016	Fine skewed	1.06	Mesokurtic
B13	1.18	Medium-grained	0.62	Moderately well sorted	0.138	Fine skewed	0.96	Mesokurtic
B18	1.18	Medium-grained	0.70	Moderately well sorted	- 0.088	Near symmetrical	0.82	Platykurtic
B21	1.13	Medium-grained	0.70	Moderately well sorted	0.016	Near symmetrical	0.97	Mesokurtic
B25	1.35	Medium-grained	0.60	Moderately well sorted	0.065	Near symmetrical	1.07	Mesokurtic
B27	1.32	Medium-grained	0.56	Moderately well sorted	0.053	Near symmetrical	1.09	Mesokurtic
B30	1.35	Medium-grained	0.51	Moderately well sorted	- 0.01	Near symmetrical	1.02	Mesokurtic
B32	1.36	Medium-grained	0.54	Moderately sorted	- 0.017	Near symmetrical	1.16	Leptokurtic
B35	1.51	Medium-grained	0.84	Moderately well sorted	0.04	Near symmetrical	1.48	Leptokurtic
B37	1.42	Medium-grained	0.69	Moderately well sorted	0.29	Fine skewed	1.04	Mesokurtic
B40	1.88	Medium-grained	0.77	Moderately sorted	0.19	Fine skewed	1.03	Mesokurtic
B42	2.08	Medium-grained	0.48	Well sorted	0.06	Near symmetrical	0.84	Platykurtic
B45	2.39	Medium-grained	0.70	Moderately well sorted	0.01	Near symmetrical	0.87	Platykurtic
B49	1.96	Medium-grained	0.77	Moderately sorted	0.09	Near symmetrical	0.91	Mesokurtic
Avg.	1.55		0.64		0.04		1.02	

Table 31. Roundness parameters of Bayana Sandstones

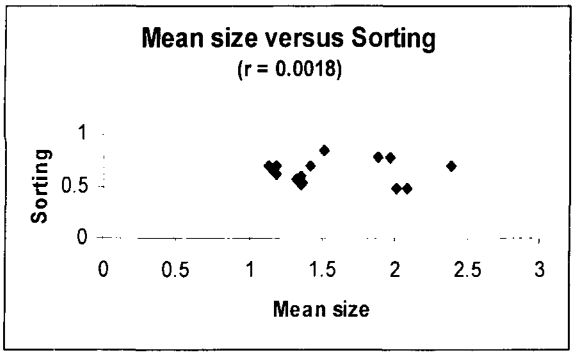
Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean Roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
B5	180	9	5	55	31	63	35	54	30	-	-	-	-	0.30
B8	106	4	4	18	17	35	33	36	34	2	1	-	-	0.29
B13	105	4	4	15	14	32	30	49	47	6	6	-	-	0.35
B18	103	-	-	28	27	24	23	23	22	8	7	-	-	0.26
B21	100	1	1	10	10	48	48	40	40	2	2	-	-	0.34
B25	110	10	9	31	28	39	35	33	30	5	4	1	0.90	0.33
B27	120	6	5	40	33	52	43	28	23	2	1	-	-	0.31
B30	110	2	2	2	18	39	35	39	35	7	6	-	-	0.33
B32	135	3	2	29	21	59	44	41	30	3	2	-	-	0.32
B35	162	12	7	30	18	65	31	50	31	4	2	1	0.61	0.31
B37	138	10	7	23	17	43	27	49	35	10	7	3	2	0.34
B40	112	5	4	18	16	30	35	40	36	17	15	2	1	0.37
B42	100	2	2	8	8	35	34	35	35	18	18	2	2	0.39
B45	96	8	8	8	8	33	37	37	39	10	10	-	-	0.35
B49	108	1	.9	12	11	40	35.7	47	44	6	5	2	1	0.36
Avg.			4.06		18.4				35.3		5.7		0.50	0.33

Table 32. Sphericity parameters of Bayana Sandstones

Sample No	Total grain	High Sphericity		Low Sphericity		Mean Sphericity
		N	%	N	%	
B5	140	31	22	109	78	0.43
B8	130	44	34	86	66	0.50
B13	120	46	38	74	62	0.53
B18	110	43	39	67	61	0.53
B21	115	35	30	80	70	0.48
B25	100	48	48	52	52	0.58
B27	115	36	31	79	69	0.48
B30	110	32	29	78	71	0.47
B32	115	36	31	79	69	0.48
B35	125	33	26	92	74	0.45
B37	132	37	28	95	72	0.46
B40	100	39	39	61	61	0.53
B42	97	42	43	55	54	0.55
B45	108	34	31	74	69	0.48
B49	112	44	39	68	59	0.53
Avg			33.8		66.13	0.49

Table 33. Textural maturity parameters of Bayana Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
B5	2.01	Medium-grained	--	0.48	Well sorted	0.30	Subangular	Submatured
B8	1.16	Medium-grained	--	0.65	Moderately well sorted	0.29	Subangular	Submatured
B13	1.18	Medium-grained	--	0.62	Moderately well sorted	0.35	Subrounded to subangular	Submatured
B18	1.18	Medium-grained	--	0.70	Moderately well sorted	0.26	Subangular	Submatured
B21	1.13	Medium-grained	--	0.70	Moderately well sorted	0.34	Subangular	Submatured
B25	1.35	Medium-grained	--	0.60	Moderately well sorted	0.33	Subangular	Submatured
B27	1.32	Medium-grained	--	0.56	Moderately well sorted	0.31	Subangular	Submatured
B30	1.35	Medium-grained	--	0.51	Moderately well sorted	0.33	Subangular	Submatured
B32	1.36	Medium-grained	--	0.54	Moderately sorted	0.32	Subangular	Submatured
B35	1.51	Medium-grained	--	0.84	Moderately well sorted	0.31	Subangular	Submatured
B37	1.42	Medium-grained	--	0.69	Moderately well sorted	0.34	Subangular	Submatured
B40	1.88	Medium-grained	--	0.77	Moderately sorted	0.37	Subrounded	Submatured
B42	2.08	Medium-grained	--	0.48	Well sorted	0.39	Subrounded	Submatured
B45	2.39	Medium-grained	--	0.70	Moderately well sorted	0.35	Subrounded to subangular	Submatured
B49	1.96	Medium-grained	--	0.77	Moderately sorted	0.36	Subrounded	Submatured



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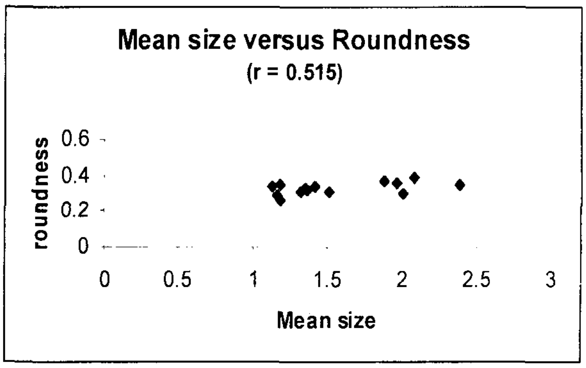

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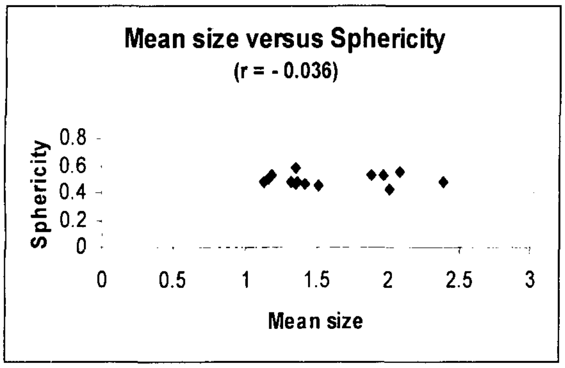

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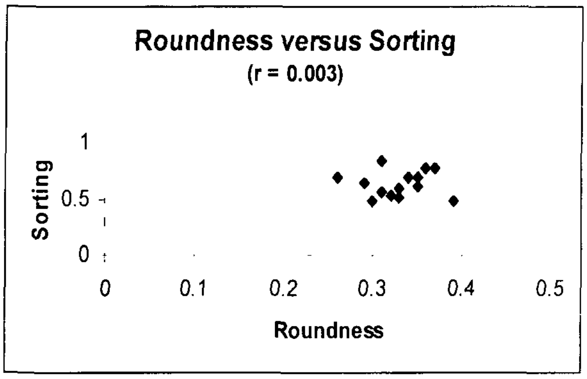

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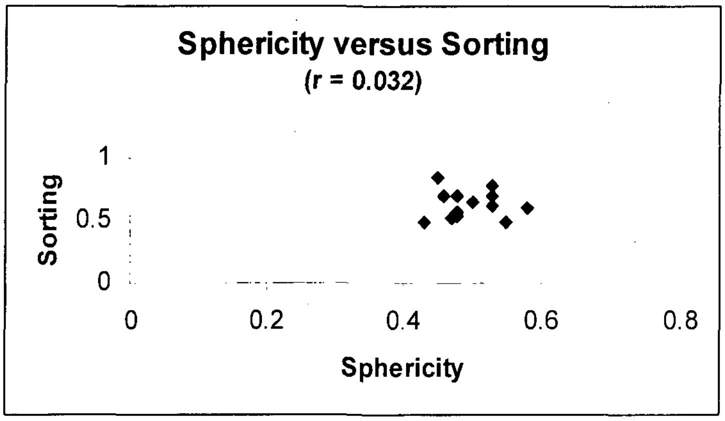

(e)

Figure 33. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Bayana Formation, Bayana Basin.

roundness ranging from very angular to well-rounded. Majority of the grains are subangular (average 37.5 %) to sub-rounded (average 34.2 %). The grains studied showed low sphericity (69.8 %) and 30.2 % is of high sphericity (Table 35). The mean sphericity values of the individual samples range from 0.41 to 0.53, average 0.49. The mean roundness of the individual samples range from 0.25 to 0.36, average being 0.32 (Table 36). . The studied sandstones are sub-mature as most of the grains are subangular to subrounded (Table 37).. Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Bhimnagar were plotted against their sorting values and their correlation coefficient value was computed (- 0.14) which shows a moderate and positive relationship (Figure 34). . The mean size versus roundness plot shows a poor and inverse relationship between the two parameters with correlation coefficient value of - 0.06. The mean size versus sphericity diagram shows a moderate but positive relationship. The correlation coefficient value is 0.21. Plotting of roundness versus sorting shows moderate and positive relationship with correlation coefficient value of - 0.11. The plot of sphericity versus sorting shows a good and positive relationship with correlation coefficient of 0.63.

Interpretation: Textural study of 15 samples of sandstones of Bayana locality and 17 samples of Bhimnagar locality of Bayana Formation shows that sandstones are medium-grained, moderately well sorted to well sorted. Their inclusive graphic skewness varies widely from coarse skewed to near symmetrical to fine skewed. The graphic kurtosis also shows variation from mesokurtic to platykurtic to leptokurtic. The grains are mostly subangular closely followed by subrounded. Most of the grains have low sphericity. Bivarient plottings of various parameters in Bayana locality show poor relationship among them while in case of Bhimnagar locality they show moderate to good relationship. Thus texturally sandstones of Bayana Formation can be considered as sub-mature.

Table 34. Grain size parameters of Bhimnagar Sandstones

Sample No.	Mz	Verbal limit	σ 1	Verbal limit	SKi	Verbal limit	Kg	Verbal limit
BN1	1.8	Medium-grained	0.83	Moderately sorted	0.098	Near symmetrical	0.99	Mesokurtic
BN3	1.8	Medium-grained	0.63	Moderately well sorted	-0.013	Near symmetrical	0.72	Platykurtic
BN5	1.71	Medium-grained	0.65	Moderately well sorted	-0.034	Near symmetrical	0.88	Platykurtic
BN8	1.65	Medium-grained	0.84	Moderately sorted	-0.088	Near symmetrical	1.06	Platykurtic
BN10	2.01	Medium-grained	0.93	Moderately sorted	-0.126	Coarse skewed	0.93	Mesokurtic
BN12	1.76	Medium-grained	0.69	Moderately well sorted	-0.08	Near symmetrical	0.78	Platykurtic
BN14	1.81	Medium-grained	0.71	Moderately well sorted	0.027	Near symmetrical	0.96	Mesokurtic
BN16	1.66	Medium-grained	0.62	Moderately well sorted	0.114	Near symmetrical	0.84	Mesokurtic
BN18	1.36	Medium-grained	0.59	Moderately well sorted	0.006	Near symmetrical	0.91	Mesokurtic
BN19	1.53	Medium-grained	0.59	Moderately well sorted	-0.046	Near symmetrical	0.91	Mesokurtic
BN20	1.31	Medium-grained	0.65	Moderately well sorted	-0.201	Coarse skewed	0.76	Mesokurtic
BN22	1.51	Medium-grained	0.84	Moderately sorted	0.04	Near symmetrical	1.48	Leptokurtic
BN24	1.51	Medium-grained	0.69	Moderately well sorted	0.29	Fine skewed	1.04	Mesokurtic
BN27	1.88	Medium-grained	0.77	Moderately sorted	0.19	Fine skewed	1.03	Mesokurtic
BN29	2.08	Medium-grained	0.48	Well sorted	0.06	Near symmetrical	0.84	Platykurtic
BN31	2.31	Medium-grained	0.70	Moderately well sorted	0.01	Near symmetrical	0.87	Platykurtic
BN33	1.96	Medium-grained	0.77	Moderately sorted	0.09	Near symmetrical	0.91	Mesokurtic
Avg	1.68		0.70		0.019		0.93	

Table 35. Sphericity parameters of Bhimnagar Sandstones

Sample No	Total grain	High Sphericity		Low Sphericity		Mean Sphericity
		N	%	N	%	
BN1	110	40	19	70	64	0.51
BN3	172	32	32	140	81	0.41
BN5	100	32	37	68	68	0.49
BN8	259	95	39	164	63	0.52
BN10	106	41	31	65	61	0.53
BN12	160	50	37	110	69	0.48
BN14	309	114	23	195	63	0.52
BN16	105	24	23	81	77	0.43
BN18	115	26	33	89	77	0.43
BN19	116	38	35	78	67	0.49
BN20	165	58	33	107	65	0.51
BN22	279	93	35	186	67	0.50
BN24	170	60	35	110	65	0.51
BN27	100	35	30	65	65	0.51
BN29	125	37	36	88	70	0.47
BN31	146	53	37	93	64	0.51
BN33	185	69	30.2	116	63	0.52
Avg					69.8	0.49

Table 36. Roundness parameters of Bhimnagar Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean Roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
BN1	105	23	21.9	20	19	24	22.8	28	26.6	10	9.5	-	-	0.30
BN3	120	16	13.3	20	16.6	27	22.5	24	20	11	9.1	2	1.6	0.27
BN5	106	18	16.9	27	25.4	23	21.6	23	21.6	4	3.7	-	-	0.25
BN8	130	9	6.9	39	30	46	35.3	42	32.3	3	2.3	1	0.7	0.33
BN10	85	4	4.7	14	16.4	34	40	30	35.2	3	3.5	-	-	0.33
BN12	100	4	4	15	15	40	40	36	36	5	5	-	-	0.33
BN14	146	5	3.4	10	6.8	58	39.7	63	43.1	8	5.4	2	1.3	0.36
BN16	118	3	2.5	22	18.6	41	34.7	47	39.8	5	4.2	-	-	0.33
BN18	109	2	1.8	17	15.5	43	39.4	40	36.6	6	5.5	1	0.9	0.34
BN19	100	7	7	13	13	40	40	35	35	4	4	1	1	0.33
BN20	120	8	6.6	20	16.6	47	39.1	38	31.6	5	4.1	2	1.6	0.33
BN22	93	3	3.2	15	16.1	38	40.8	32	34.4	3	3.2	2	2.1	0.34
BN24	112	5	4.4	15	13.3	49	43.7	40	35.7	3	2.6	-	-	0.33
BN27	135	1	0.7	13	9.6	50	37.0	60	44.4	4	2.9	2	1.4	0.34
BN29	138	3	2.1	15	10.8	65	47.1	53	38.4	2	1.4	-	-	0.33
BN31	103	--	--	12	11.6	52	50.4	38	36.8	1	0.9	-	-	0.33
BN33	100	2	2	18	18	45	45	35	35	--	-	-	-	0.32
Avg			6.7		16		37.5		34.2		3.9		0.62	0.32

Table 37. Textural maturity parameters of Bhimnagar Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
BN1	1.8	Medium-grained	--	0.83	Moderately sorted	0.30	Subangular	Submatured
BN3	1.8	Medium-grained	--	0.63	Moderately well sorted	0.27	Subangular	Submatured
BN5	1.71	Medium-grained	--	0.65	Moderately well sorted	0.25	Subangular	Submatured
BN8	1.65	Medium-grained	--	0.84	Moderately sorted	0.33	Subangular	Submatured
BN10	2.01	Medium-grained	--	0.93	Moderately sorted	0.33	Subangular	Submatured
BN12	1.76	Medium-grained	--	0.69	Moderately well sorted	0.33	Subangular	Submatured
BN14	1.81	Medium-grained	--	0.71	Moderately well sorted	0.36	Subangular	Submatured
BN16	1.66	Medium-grained	--	0.62	Moderately well sorted	0.33	Subrounded	Submatured
BN18	1.36	Medium-grained	--	0.59	Moderately well sorted	0.34	Subangular	Submatured
BN19	1.53	Medium-grained	--	0.59	Moderately well sorted	0.33	Subangular	Submatured
BN20	1.31	Medium-grained	--	0.65	Moderately well sorted	0.33	Subangular	Submatured
BN22	1.51	Medium-grained	--	0.84	Moderately sorted	0.34	Subangular	Submatured
BN24	1.51	Medium-grained	--	0.69	Moderately well sorted	0.33	Subangular	Submatured
BN27	1.88	Medium-grained	--	0.77	Moderately sorted	0.34	subangular	Submatured
BN29	2.08	Medium-grained	--	0.48	Well sorted	0.33	Subangular	Submatured
BN31	2.31	Medium-grained		0.70	Moderately well sorted	0.33	Subangular	Submatured
BN33	1.96	Medium-grained		0.77	Moderately sorted	0.32	Subangular	Submatured

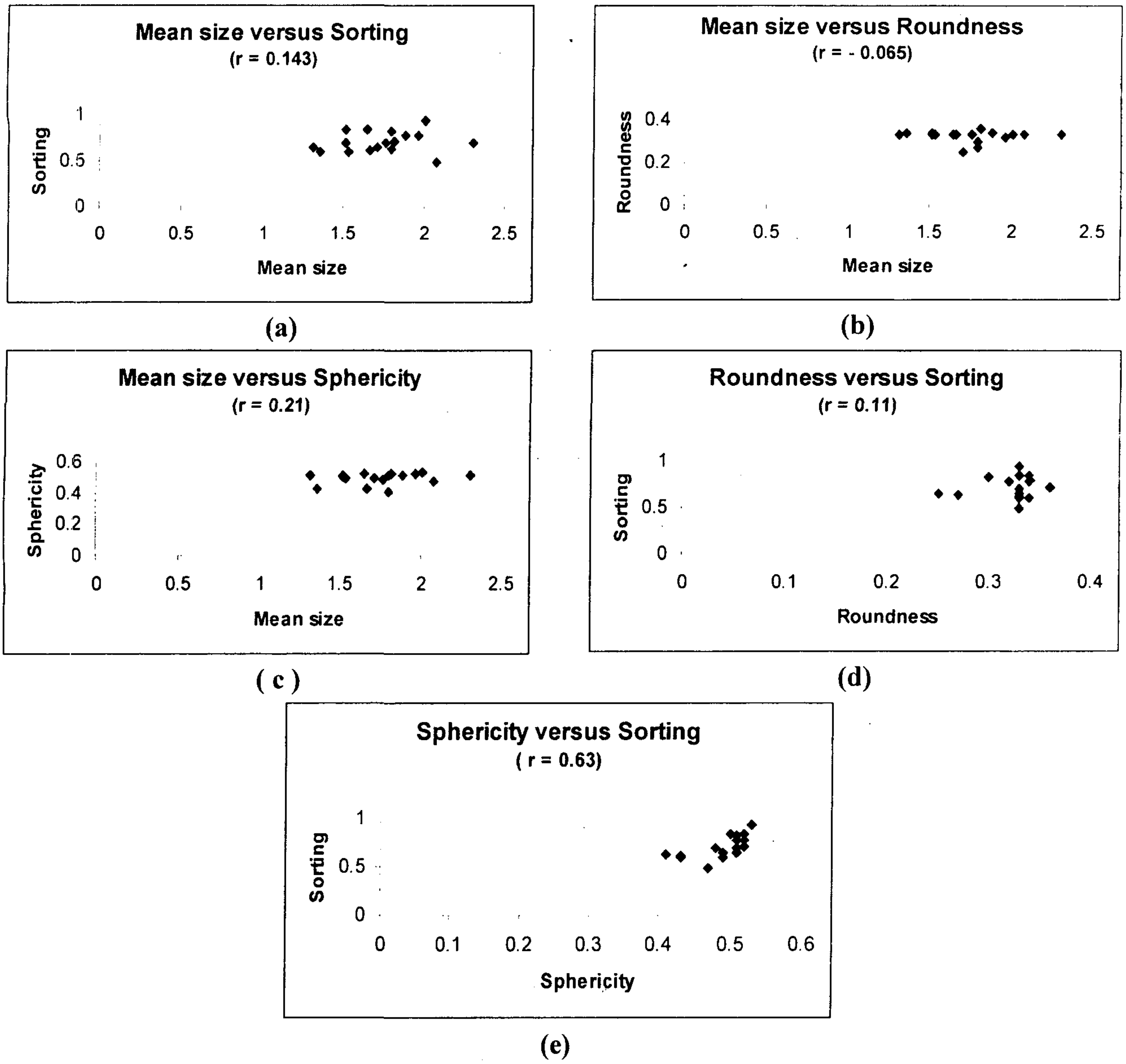

Figure 34. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Bhimnagar of Bayana Formation, Bayana Basin.

UMRAIND SANDSTONES
(Damdama Formation)

The mean size of the Umraind Sandstones range from 1.03 Φ to 2.29 Φ, average 1.72 Φ, indicating medium-grains (Table 38). The **σ I** values of the Umraind sandstones range from 0.58 Φ to 0.82 Φ indicating moderately sorted to moderately well sorted nature, average is 0.13 Φ. **Ski** values of the sandstones of the Umraind locality of Damdama Formation ranges from – 0.02 to 0.25, average being 0.013. The samples vary from near symmetrical to fine skewed. The $\mathbf{K_G}$ values of the studied sandstones range from 0.81 to 1.25, average being 1.04 indicating variation from mesokurtic to leptokurtic followed by platykurtic. Most of the grains studied showed high sphericity (52.7 %) and 47.3 % is of low sphericity (Table 39).. The mean sphericity values of the individual samples range from 0.51 to 0.68, average 0.61. The grain roundness ranges from angular to rounded. Majority of the grains are subrounded (avg. 56.9 %) to subangular (avg. 38 %) (Table 40). The mean roundness of the individual samples range from 0.34 to 0.37, average being 0.36. The studied sandstones are sub-mature as most of the grains are subangular to sub-rounded (Table 41).Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Umraind were plotted against their sorting values and their correlation coefficient value was computed (- 0.60) which shows a good but inverse relationship (Figure 35).. The mean size versus roundness plot shows a poor and inverse relationship between the two parameters with correlation coefficient value of - 0.06. The mean size versus sphericity diagram shows a moderate but inverse relationship. The correlation coefficient value is - 0.34. Plotting of roundness versus sorting shows moderate and inverse relationship with correlation coefficient value of - 0.34. The plot of sphericity versus sorting shows a moderate and positive relationship with correlation coefficient of 0.43.

Table 38. Grain size parameters of Umraind Sandstones

Sample No.	Mz	Verbal limit	σ I	Verbal limit	SKi	Verbal limit	Kg	Verbal limit
U1	1.21	Medium-grained	0.82	Moderately sorted	0.25	Fine skewed	0.81	Platykurtic
U3	1.03	Medium-grained	0.80	Moderately sorted	-0.21	Fine skewed	0.88	Platykurtic
U5	1.90	Medium-grained	0.78	Moderately sorted	-0.02	Near symmetrical	0.91	Mesokurtic
U6	2.03	Medium-grained	0.72	Moderately sorted	0.16	Fine skewed	1.25	Leptokurtic
U8	2.29	Medium-grained	0.58	Moderately well sorted	0.22	Fine skewed	1.09	Mesokurtic
U9	1.60	Medium-grained	0.66	Moderately well sorted	-0.04	Fine skewed	1.15	Leptokurtic
U10	2.00	Medium-grained	0.79	Moderately sorted	0.14	Fine skewed	1.25	Leptokurtic
Avg.	1.72		0.73		0.13		1.04	

Table 39. Sphericity parameters of Umraind Sandstones

Sample No	Total grain	High Sphericity		Low Sphericity		Mean Sphericity
		N	%	N	%	
U1	162	90	55.5	72	44.5	0.63
U3	154	93	60.3	61	39.6	0.66
U5	113	72	63.7	41	36.2	0.68
U6	122	43	35.2	79	64.7	0.51
U8	149	77	51.6	72	48.3	0.61
U9	133	63	47.3	70	52.6	0.58
U10	110	61	55.4	49	44.5	0.63
Avg.			52.7		47.3	0.61

Table 40. Roundness parameters of Umraind Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean Roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
U1	162	-	-	5	3	56	34.5	96	59.2	5	3	-	-	0.37
U3	154	-	-	3	1.9	60	38.9	91	59	-	-	-	-	0.36
U5	113	-	-	4	3.5	44	38.9	64	56.6	1	0.8	-	-	0.36
U6	122	-	-	-	-	45	36.8	76	62.2	1	0.8	-	-	0.37
U8	149	-	-	8	5.3	42	28.1	96	64.4	3	2.0	-	-	0.37
U9	133	-	-	6	4.5	52	39	73	54.8	2	1.5	-	-	0.36
U10	110	-	-	7	6.3	55	50	47	42.7	1	0.9	-	-	0.34
Avg.					3.5		38		56.9		1.28			0.36

Table 41. Textural maturity parameters of Umraind Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
U1	1.21	Medium-grained	--	0.82	Moderately sorted	0.37	Subrounded	Submatured
U3	1.03	Medium-grained	--	0.80	Moderately sorted	0.36	Subrounded	Submatured
U5	1.90	Medium-grained	--	0.78	Moderately sorted	0.36	Subrounded	Submatured
U6	2.03	Medium-grained	--	0.72	Moderately sorted	0.37	Subrounded	Submatured
U8	2.29	Medium-grained	--	0.58	Moderately well sorted	0.37	Subrounded	Submatured
U9	1.60	Medium-grained	--	0.66	Moderately well sorted	0.36	Subrounded	Submatured
U10	2.00	Medium-grained	--	0.79	Moderately sorted	0.34	Subangular	Submatured

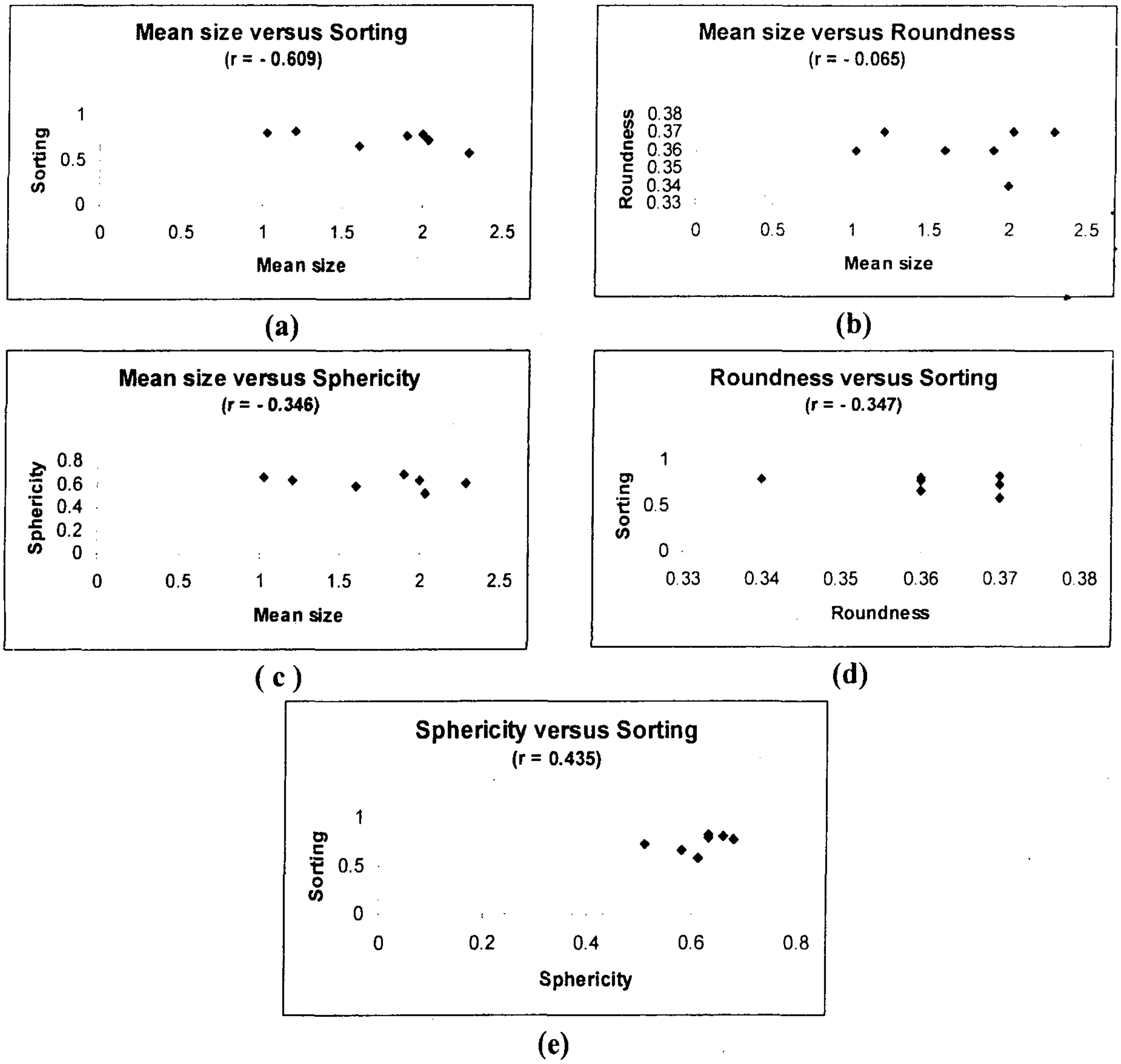

Figure 35. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Umraind of Damdama Formation, Bayana Basin.

KANAWAR SANDSTONES
(Damdama Formation)

The Mz values of the Kanawar Sandstones range from 1.21 Φ to 2.29 Φ, average 1.89 Φ, indicating medium-grained. The **σ I** values of the Kanawar Sandstones range from 0.58 Φ to 0.83 Φ indicating moderately sorted to moderately well sorted nature, average is 0.72 Φ. The **Ski** values of the sandstones of the kanawar locality of Damdama Formation ranges from – 0.01 to 0.31, average being 0.067. The samples vary from near symmetrical to fine skewed (Table 42). The $\mathbf{K_G}$ values of the studied sandstones range from 0.67 to 0.97, average being 1.83 indicating variation from mesokurtic to leptokurtic followed by platykurtic. Most of the grains studied show low sphericity (69 %) and 31 % is of high sphericity (Table 43). The mean sphericity values of the individual samples range from 0.44 to 0.53, average 0.48. The grain roundness ranges from angular to rounded. Majority of the grains are subrounded (average 52.3 %) to subangular (average 38.2 %) (Table 44). The mean roundness of the individual samples range from 0.35 to 0.37, average being 0.35. The studied sandstones are sub-mature as most of the grains are subangular to subrounded (Table 45). Absence of clay indicates that the sandstones were deposited under high energy environment.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Kanawar were plotted against their sorting values and their correlation coefficient value was computed (- 0.24) which shows a moderate but inverse relationship (Figure 36). . The mean size versus roundness plot shows a moderate and inverse relationship between the two parameters with correlation co-efficient value of - 0.43. The mean size versus sphericity diagram shows a good and positive relationship. The correlation coefficient value is 0.82. Roundness versus sorting plot shows good and positive relationship with correlation co-efficient value of 0.7. The plot of sphericity versus sorting shows a moderate and inverse relationship with correlation coefficient of - 0.20.

Table 42. Grain size parameters of Kanawar Sandstones

Sample No.	Mz	Verbal limit	σ I	Verbal limit	SKi	Verbal limit	K_G	Verbal limit
K1	1.21	Medium-grained	0.83	Moderately sorted	0.25	Fine skewed	0.81	Platykurtic
K2	1.90	Medium-grained	0.78	Moderately sorted	0.31	Fine skewed	0.91	Mesokurtic
K4	1.77	Medium-grained	0.58	Moderately Well sorted	-0.02	Near symmetrical	0.97	Mesokurtic
K6	2.03	Medium-grained	0.64	Moderately Well sorted	- 0.01	Near symmetrical	0.69	Platykurtic
K8	2.19	Medium-grained	0.72	Moderately sorted	- 0.01	Near symmetrical	0.67	Platykurtic
K9	2.29	Medium-grained	0.78	Moderately sorted	-0.10	Near symmetrical	0.93	Leptokurtic
Avg.	1.89		0.72		0.067		0.83	

Table 43. Sphericity of Kanawar Sandstones

Sample No	Total grain	High Sphericity		Low Sphericity		Mean Sphericity
		N	%	N	%	
K1	110	26	23.6	84	76.4	0.44
K2	102	31	30.3	71	69.6	0.48
K4	130	42	32.3	88	67.7	0.49
K6	128	39	30.4	89	69.5	0.48
K8	115	35	30.4	80	69.5	0.48
K9	105	41	39	64	60.9	0.53
Avg.			31		69	0.48

Table 44. Roundness of Kanawar Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
K1	102	-	-	10	9.8	28	27.5	58	56.8	6	58	-	-	0.37
K2	107	-	-	11	10.2	40	37.3	53	49.5	3	2.8	-	-	0.35
K4	121	-	-	9	7.4	50	41.3	60	49.5	2	1.6	-	-	0.35
K6	102	-	-	10	9.8	40	39.2	51	50	1	0.9	-	-	0.35
K8	118	-	-	3	2.5	50	42.3	65	55	-	-	-	-	0.36
K9	120	-	-	5	4.1	50	41.6	64	53.3	1	0.8	-	-	0.36
Avg.					7.3		38.2		52.3		1.9			0.35

Table 45. Textural maturity of Kanawar Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
K1	1.21	Medium-grained	--	0.83	Moderately sorted	0.37	Subrounded	Submatured
K2	1.90	Medium-grained	--	0.78	Moderately sorted	0.35	Subrounded to subangular	Submatured
K4	1.77	Medium-grained	--	0.58	Moderately well sorted	0.35	Subrounded to subangular	Submatured
K6	2.03	Medium-grained	--	0.64	Moderately sorted	0.35	Subrounded to subangular	Submatured
K8	2.19	Medium-grained	--	0.72	Moderately well sorted	0.36	Subrounded	Submatured
K9	2.29	Medium-grained	--	0.78	Moderately well sorted	0.36	Subrounded	Submatured

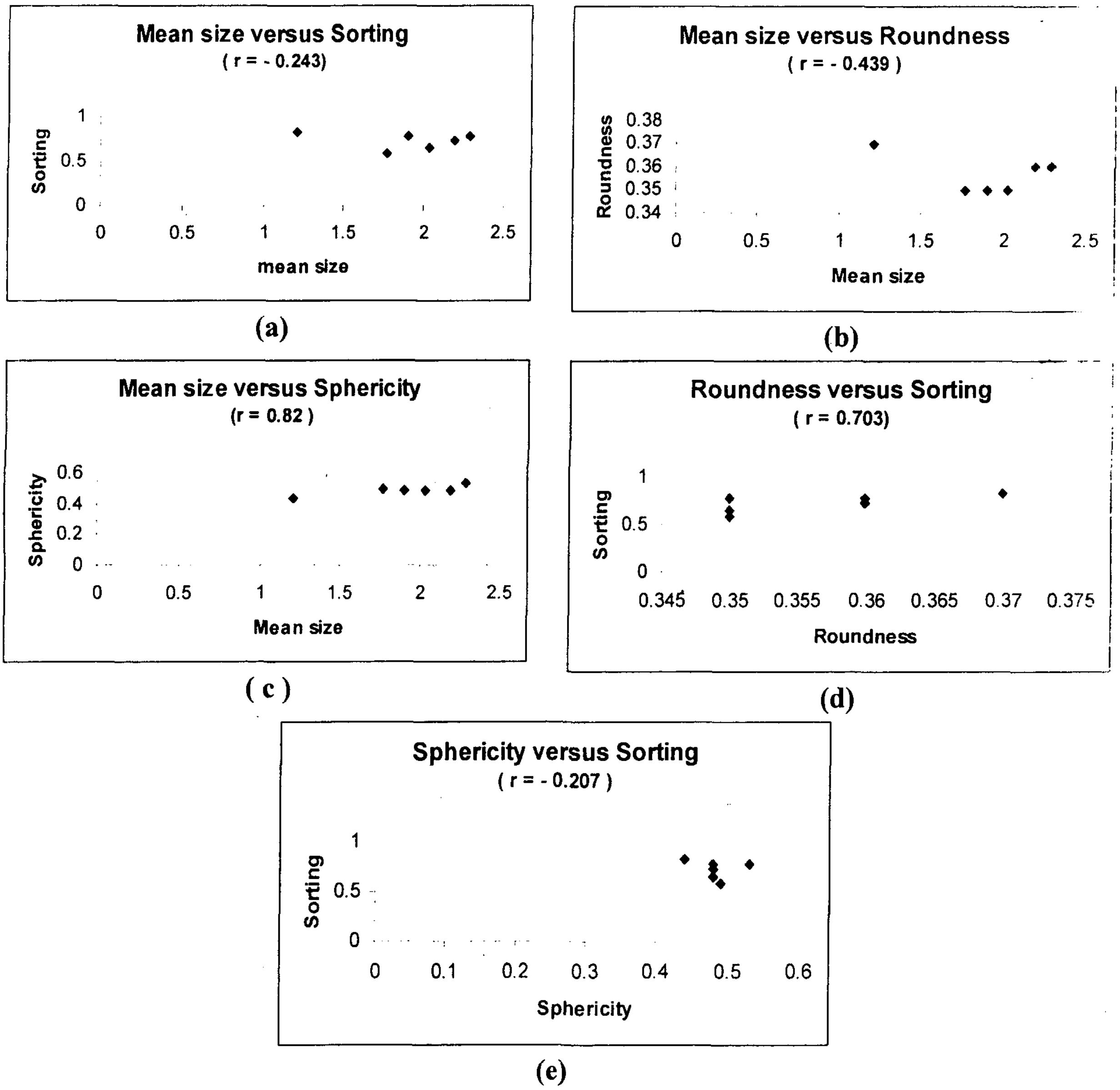

Figure 36. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Kanawar of Damdama Formation, Bayana Basin.

Interpretation : Analysis of 7 samples of Umraind and 6 samples of Kanawar localities of Damdama Formation shows that sandstones are medium-grained, moderately sorted, near symmetrical to fine skewed and vary from mesokurtic to platykurtic to leptokurtic in the scale of inclusive graphic kurtosis. Most of the grains are subrounded to subangular and have low sphericity. Bivarient plotting indicates that relationship between mean size versus sorting is moderate to good, mean size versus roundness is poor to moderate, mean size versus sphericity is moderate to good, roundness versus sorting is moderate to good, and finally sphericity versus sorting is moderate. Thus texturally the sandstones of Damdama Formation can be considered as sub-mature.

WEIR SANDSTONES
(Weir Formation)

The Mz value of the sandstones of Weir Formation range from 1.41 Φ to 2.36 Φ, average 1.87 Φ, indicating medium-grains (Table 46). The **σ I** values of the Weir Sandstones range from 0.44 Φ to 0.78 Φ indicating moderately sorted to well sorted nature, average is 0.56 Φ. The **Ski** values of the sandstones of Weir Formation ranges from – 0.13 to 0.38, average being - 0.20. The samples vary from coarse skewed to fine skewed. The $\mathbf{K_G}$ values of the studied sandstones range from 0.92 to 1.83, average being 1.29 indicating variation from mesokurtic to leptokurtic. Most of the grains studied showed low sphericity (54.8 %) and 45.1 % is of high sphericity (Table 47). The mean sphericity values of the individual samples range from 0.53 to 0.62, average 0.56. The sandstones have grain roundness ranging from very angular to well rounded (Table 48). Majority of the grains are subrounded (average 40.57 %) to subangular (average 40.14 %). The mean roundness of the individual samples range from 0.34 to 0.37, average being 0.35. The studied sandstones are sub-mature (Table 49) as most of the grains are subangular to subrounded. Absence of clay indicates that the sandstones were deposited under high energy environment.

Table 46. Grain size parameters of Weir Sandstones

Sample No.	**Mz**	**Verbal limit**	**σ I**	**Verbal limit**	**SKi**	**Verbal limit**	**K_G**	**Verbal limit**
W1	2.25	Medium-grained	0.48	Well sorted	- 0.21	Coarse skewed	1.35	Leptokurtic
W2	1.85	Medium-grained	0.48	Well sorted	- 0.15	Coarse skewed	0.96	Mesokurtic
W3	2.36	Medium-grained	0.51	Moderately Well sorted	- 0.23	Coarse skewed	1.19	Leptokurtic
W4	2.1	Medium-grained	0.44	Well sorted	- 0.13	Coarse skewed	0.92	Mesokurtic
W5	1.63	Medium-grained	0.58	Moderately Well sorted	0.09	Near symmetrical	1.77	Very Leptokurtic
W6	1.51	Medium-grained	0.69	Moderately Wellsorted	0.38	Strongly fine skewed	1.83	Very Leptokurtic
W7	1.41	Medium-grained	0.78	Moderately sorted	0.24	Fine skewed	1.06	Mesokurtic
Avg.	1.87		0.56		- 0.20		1.29	

Table 47. Sphericity parameters of Weir Sandstones

Sample No	**Total grain**	**High Sphericity**		**Low Sphericity**		**Mean Sphericity**
		N	%	N	%	
W1	125	60	48	65	52	0.58
W2	100	44	44	56	56	0.56
W3	110	56	51	54	49	0.60
W4	100	41	41	59	59	0.54
W5	135	72	53	63	47	0.62
W6	116	48	41	68	59	0.54
W7	120	46	38	74	62	0.53
Avg.			45.1		54.8	0.56

Table 48. Roundness parameters of Weir Sandstones

Sample No.	Total grain	Very angular		Angular		Subangular		Subrounded		Rounded		Well Rounded		Mean Roundness
		N	%	N	%	N	%	N	%	N	%	N	%	
W1	100	-	-	13	13	41	41	42	42	4	4	-	-	0.35
W2	110	1	1	15	14	44	40	44	40	5	4	1	1	0.35
W3	105	-	-	12	11	43	41	44	42	5	5	1	1	0.35
W4	100	4	4	14	14	36	36	36	36	10	10	-	-	0.35
W5	125	2	1	18	14	39	39	49	39	6	4	1	1	0.34
W6	118	1	1	10	9	49	41	49	41	8	7	1	1	0.36
W7	102	4	4	8	7	49	43	45	44	5	5	1	1	0.37
Av.			1.7		11.7	45	40.14		40.57		5.57		0.71	0.35

Table 49. Textural maturity parameters of Weir Sandstones

Sample No	Mean size (Ø)		Clay	Sorting (Ø)		Mean roundness of grains		Maturity
W1	2.25	Medium-grained	--	0.48	Well sorted	0.35	Subrounded	Submatured
W2	1.85	Medium-grained	--	0.48	Well sorted	0.35	Subrounded	Submatured
W3	2.36	Medium-grained	--	0.51	Moderately well sorted	0.35	Subrounded	Submatured
W4	2.1	Medium-grained	--	0.44	Well sorted	0.35	Subrounded	Submatured
W5	1.63	Medium-grained	--	0.58	Moderately well sorted	0.34	Subangular	Submatured
W6	1.51	Medium-grained	--	0.69	Moderately well sorted	0.36	Subrounded	Submatured
W7	1.41	Medium-grained	--	0.78	Moderately sorted	0.37	Subrounded	Submatured

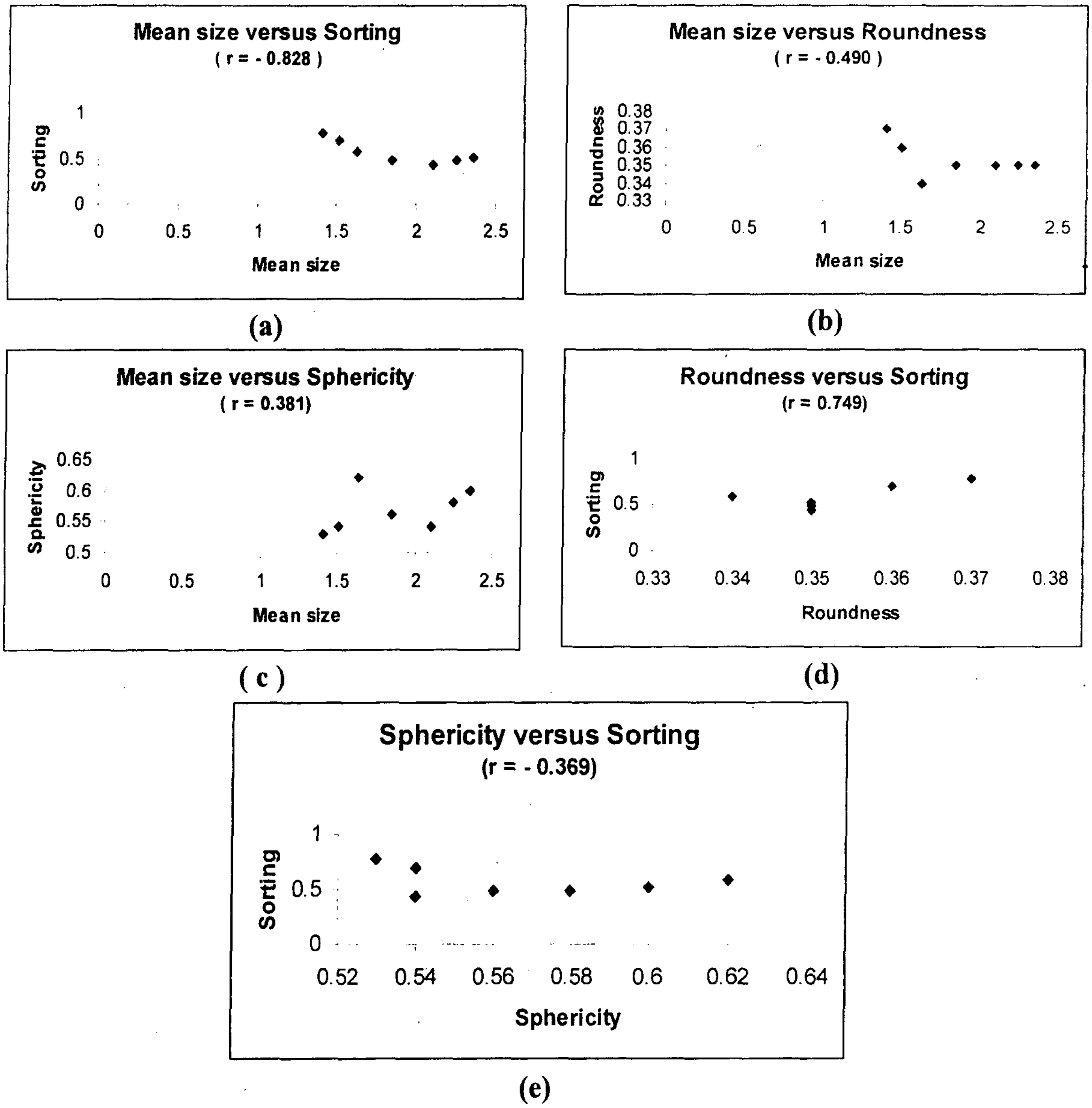

Figure 37. Bivarient plot of (a) Mean-size versus Sorting (b) Mean-size versus Roundness (c) Mean-size versus Sphericity (d) Sphericity versus Sorting (e) Roundness versus Sorting of sandstones of Weir Formation, Bayana Basin.

Bivarient plots of textural parameters:

The mean size of sandstone samples of Weir were plotted against their sorting values and their correlation coefficient value was computed (- 0.82) which shows a good but inverse relationship (Figure 37). The mean size versus roundness plot shows a moderate and inverse relationship between the two parameters with correlation co- efficient value of - 0.49. The mean size versus sphericity diagram shows a moderate and positive relationship. The correlation coefficient value is 0.38. Plotting of roundness versus sorting shows good and positive relationship with correlation coefficient value of 0.74. The plot of sphericity versus sorting shows a moderate and inverse relationship with correlation coefficient of - 0.36.

Interpretation: Textural study of 7 sandstone samples of Weir Formation showed that sandstones are medium-grained, moderately well sorted to well sorted, coarse skewed to fine skewed and mesokurtic to leptokurtic. Most of the grains are subangular to subrounded and have low sphericity. Bivarient plotting revealed good (positive or inverse) relationship between mean size versus sorting and roundness versus sorting while moderate (positive or inverse) relationship is shown by mean size versus roundness, mean size versus sphericity and sphericity versus sorting. Thus Weir sandstones can be considered as texturally sub-mature.

Thus, petrographic studies carried out in the study area reveal that average grain-size of the Bayan basin sandstone is 2.04 Φ, grains are moderately well sorted. Most of the grains are subangular to subrounded and have low sphericity. Bivarient plotting of various parameters shows the relationship between mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting as moderate (positive as well as inverse). Overall texture of the Bayana Basin sandstones can be considered as sub-mature.

Detrital Mineralogy

CHAPTER - V

DETRITAL MINERALOGY

Sandstones are mixtures of mineral grains and rock fragments coming from naturally disintegrated products of erosion of rocks of all kinds. The entire lithosection in any given eroding watershed may be represented in the sediments. Minerals may be destroyed or altered by the weathering or during transportation enroute to the sedimentation site or by diagenesis. Because the detrital mineralogy of sandstone is the inheritance from the source area, its study is one of the most pragmatic approaches which is used to reconstruct the provenance. Studies have revealed that sandstone mineralogy is influenced by tectonic setting (Dickinson and Suczek, 1979, Ingersoll and Suczek, 1979; Dickinson, 1985; Valloni, 1985), transport mechanism, (Lucchi,1985; Velbel, 1985), effect of climate (Suttner, 1974; Mack,1984; Basu, 1985; Suttner and Dutta, 1986; Akhtar and Ahmad, 1991) and diagenetic modification (McBride,1985; Akhtar et al.,1992; Ahmad et al. , 2004; Ahmad and Bhatt, 2006; Ahmad et al., 2008).

METHODS OF STUDY

In the present study detrital mineral composition of sandstones was evaluated both qualitatively and quantitatively in 106 thin sections. The samples were selected in such a way that lateral and vertical variations within all formations are uniformly controlled. For quantitative analysis about 300-400 points per thin section were counted for determining the modal composition of rocks under investigation. Terminology of Krynine (1940) and Folk (1980) was adopted for describing several varieties of quartz and other framework constituents. Heavy minerals were separated by Milner's (1962) method.

DETRITAL MINERAL COMPOSITION

The studied sandstones are mainly composed of several varieties of quartz followed by feldspars, rock fragments, micas and heavy minerals. Average detrital mineralogy in the studied sandstone includes monocrystalline quartz (84.69 %), polycrystalline recrystalized metamorphic quartz (4.18 %), stretched metamorphic quartz (2.36 %), feldspar (3.98 %), rock fragments (3.43 %), mica (1.09 %), and heavy minerals (0.27%).

QUARTZ

Quartz is the most dominant constituent. Its varieties have been recognized on the basis of Folk's (1980) classification system. Most of the quartz grains are monocrystalline, alongwith some polycrystalline grains. The monocrystalline quartz generally shows undulatory extinction. Polycrystalline quartz grains possess both sharp and sutured intercrystalline boundaries. The varieties recorded are: common quartz, vein quartz, recrystallized metamorphic quartz and stretched metamorphic quartz. The average percentages of different quartz types are: common quartz, 84.68 %, recrystalized metamorphic quartz 4.18 %, stretched metamorphic quartz 2.36 % and vein quartz 0.01 %.

COMMON QUARTZ

Common quartz percentage varies from 58.51 % to 96.7 %, average at 84.68 %. It occurs as subsequent grain with subangular to subrounded nature. The grains are monocrystalline and present a clear appearance having few inclusions of tourmaline, mica and opaques. The grains show straight to slightly undulose extinction.

VEIN QUARTZ

It occurs in very few samples as monocrystalline grains with abundant vacuoles and cloudy appearance. It constitutes on an average 0.01 % of the total detrital fraction.

RECRYSTALLIZED METAMORPHIC QUARTZ

It occurs mainly as polycrystallised, composite grains of subsequent to equant shape. It ranges from 0.3 % to 5.54 % . The grains are made up of a mosaic of microcrystalline to fine-grained sub-individuals. The sub-individuals are equidimentional with straight boundaries, widely different optical orientation, and straight extinction

STRETCHED METAMORPHIC QUARTZ

It comprises 0.1% to 2.10 % of the detrital fraction. The grains are polycrystalline and are mostly platy to elongate. The sub-individual shows almost sub-parallel to parallel orientation, sutured boundaries and highly undulose extinction. Sometimes, the sub-individuals occur independently as microcrystalline grains which are easily recognized and distinguished from monocrystalline common quartz by characteristic features, such as elongated and lensoid shape, abundant healed fractures and highly undulose extinction.

FELDSPARS

Feldspars are next in abundance after quartz, averaging about 3.98 % of the detrital constituents. Three varieties of feldspar have been recognized which include orthoclase, plagioclase and microcline (Photo 14). The orthoclase and microcline grains are generally sub-equant with mostly subrounded to well rounded outlines. Some angular to subangular grains also occur. Both fresh and altered varieties of feldspars are present in the studied sandstones

ROCK FRAGMENTS

Rock fragments occur 0.36 % to 10.16% of the detrital fraction and average is 3.43 %. Rock fragments include siltstone, phyllite, chert (Photo15), shale, schist, quartzite and gneiss. Rarely granite and volcanic lithic fragments do occur in the studied sandstones.

MICAS

Both biotite and muscovite occur as tiny to large elongated flakes with frayed ends (Photo 16). The percentage of micas ranges from 0.045 to 3.45 %

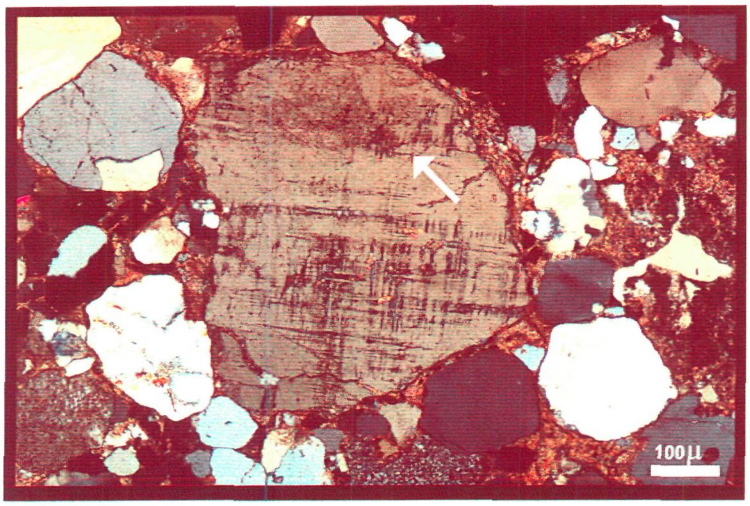

Photo 14. Microphotograph showing microcline faldspar in Kanawar Sandstones of Damdama Formation.

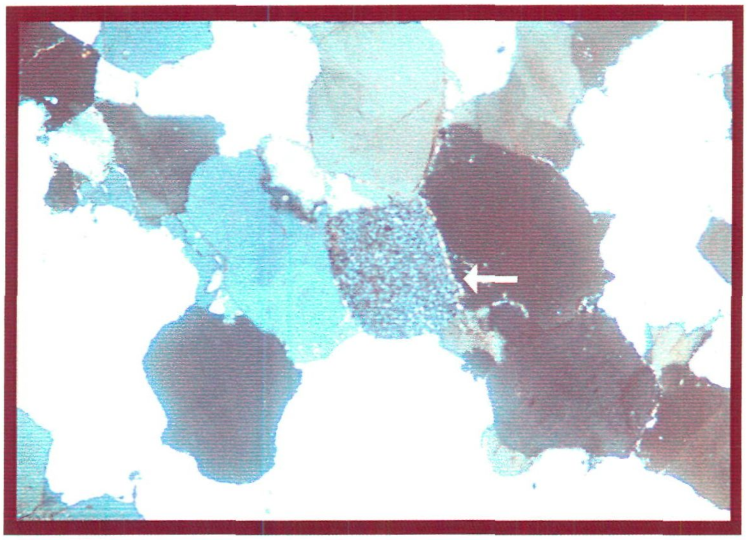

Photo 15. Microphotograph showing a chert grain in Alapuri sandstones of Badalgarh Formation

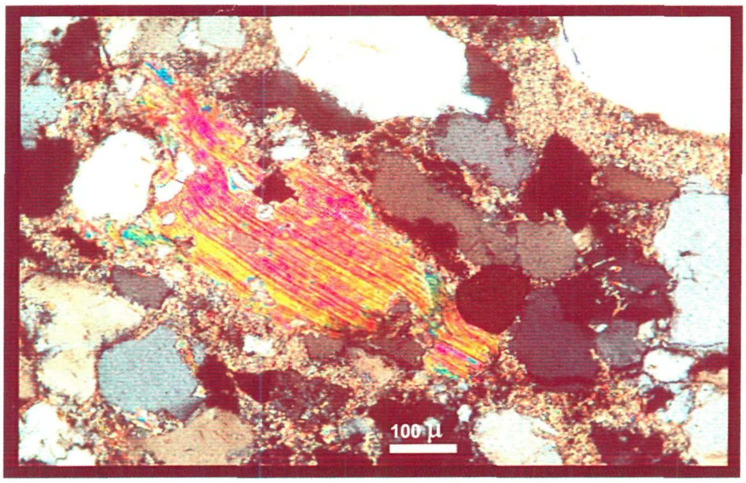

Photo 16. Microphotograph showing deformation of mica in Bhagrain sandstones of Badalgarh Formation

averaging 1.09 %. Biotite grains belong to two varieties and are green and yellow colored. Mica grains usually show the effect of compaction.

HEAVY MINERALS

In general, heavy minerals are scarce in Bayana Basin sandstones. Percentages of the heavy minerals are converted to 100%. They include opaques (87.6 %), tourmaline (3.35 %), biotite (3.1 %), muscovite (2.5 %), garnet (1.0 %), epidote (0.5%), zircon (0.5%), rutile (0.5%), and staurolite (0.5%). An average composition of heavy minerals is 0.27%.

Opaques occur mostly as subangular to subrounded grains. They include hematite, limonite and magnetite. In plane polarized light hematite appears reddish colored while limonite and magnetite appears as yellowish brown and silvery grey respectively. The grains are generally subangular to subrounded.

Tourmaline occurs as subrounded to well-rounded prismatic grains. The green variety is dominant while pale brown to dark brown are less common.

Biotite grains are prismatic or subrounded with irregular outlines. Pale brown variety of biotite is common.

Muscovite grains are colorless and occur in the form of thin flakes. The flakes are angular to sub-angular but rounded flakes are also present.

Garnet occurs as subangular to subrounded grain. The most abundant variety being light pink-colored followed by light yellow and colorless types.

Epidote occurs as irregular, subangular to subrounded grains. Pale greenish and dark varieties have been identified.

Zircon grains are pyramidal in shape with angular to subrounded boundaries. The most common variety is colorless. They contain some inclusions of opaque and other minerals.

Rutile occurs as elongated, subangular to rounded grains. It is reddish to blood-red in color.

Staurolite occurs as subangular to subrounded grains, with sub-conchoidal fractures. It is mostly yellow in color.

Detailed description of sandstone composition belonging to different formations is as follows:

Nithar Sandstones

Ten (10) samples of sandstone were obtained from thick-bedded, hard and compact, medium to fine-grained sandstones. Detrital mineralogy includes monocrystalline quartz (91.96%), polycrystalline recrystalized quartz (0.62%), stretched metamorphic quartz (1.44%), feldspar (4.19%), mica (0.04%), rock fragments (1.08%) and heavy minerals (0.27%). Average compositions of heavy minerals in these samples are as follows: opaques (78%), tourmaline (10%), muscovite (6.0%), biotite (5%), garnet (0.5%) and epidote (0.5%) (Table 50).

Jahaj-Govindpura Volcanic Sandstones

19 sandstone samples of Jahaj-Govindpura Volcanic Formation are studied. The sandstones were sampled from thick-bedded, hard and compact, medium to fine-grained tuffacious sandstones. Detrital mineralogy includes monocrystalline quartz (64.79%), polycrystalline recrystalized metamorphic quartz (1.33%), stretched metamorphic quartz (1.63%), feldspar (7.54%), mica (0.33%), rock fragments (10.19%) and heavy minerals (0.05%) (Table 51).

Table 50 . Mineralogical composition of Nithar Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic	Stretched metamorphic			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
N4	93.59	-	0.32	1.61	-	-	-	3.2	0.32	-	-	0.32	-	-	0.64
N6	93.9	-	0.55	1.65	-	-	-	3.9	-	-	-	-	-	-	-
N9	92.8	-	0.45	0.90	-	-	-	3.6	1.35	-	-	0.90	-	-	-
N12	88.7	-	1.70	2.0	0.7	0.4	0.8	2.0	2.0	-	-	1.90	-	-	0.5
N14	93.20	-	0.80	2.0	-	-	0.4	2.4	1.2	-	-	-	-	-	-
N17	90.14	-	0.21	1.9	0.8	-	-	2.3	2.8	-	-	1.2	-	-	0.65
N19	93.17	-	0.73	0.9	-	-	-	1.8	3.4	-	-	-	-	-	-
N21	89.90	-	0.17	1.25	-	-	0.7	2.8	1.97	-	-	2.3	-	-	0.91
N22	90.46	-	0.51	1.33	-	-	-	3.2	2.0	-	-	2.5	-	-	-
N23	93.63	-	0.77	0.9	-	-	-	2.6	-	-	-	2.1	-	-	-

Table 51. Minerological composition of JGV Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common Quartz	Vein Quartz	Recrystalized metamorphic quartz	Stretched metamorphic quartz			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
V1	48.71	1.5	-	1.12	0.9	0.6	5.75	1.81	1.21	10	12.1	-	-	16.3	-
V3	51.03	-	1.22	1.60	-	.58	3.00	1.07	0.7	8	13.8	-	-	19.0	-
V5	55.49	-	1.61	2.21	0.6	0.6	9.71	1.69	0.96	4.2	8.03	-	2.9	12.0	-
V7	39.07	0.5	0.57	1.73	5.7	0.5	0.88	0.57	-	4.9	12.7	-	17.6	15.0	0.28
V9	58.71	-	2.4	3.9	1.2	0.6	10.9	1.90	-	-	3.89	-	2.1	14.4	-
V11	57.53	0.5	3.5	2.32	1.2	1.2	8.10	1.72	-	-	7.23	-	3.2	13.5	-
V12	60.77	-	-	0.98	1.6	-	1.63	1.63	0.99	2.2	12.0	-	1.9	16.3	-
V14	54.99	-	1.72	1.70	0.7	0.6	7.9	1.74	2.81	5.1	3.34	-	1.0	18.4	-
V15	45.03	-	3.67	4.32	-	-	8.82	1.83	0.97	8.1	6.96	-	1.2	19.1	-
V17	75.15	-	-	1.52	0.6	0.8	1.18	1.63	0.37	3.8	0.64	-	-	13.5	0.81
V19	56.61	-	1.72	-	-	-	8.91	1.34	1.60	3.32	10.1	-	-	16.4	-
V21	54.40	-	1.22	-	-	-	3.90	2.91	1.73	9	8.34	-	1.0	17.5	-
V23	68.91	-	-	-	1.6	-	1.14	1.63	0.76	3.4	7.66	0.7	-	19.2	-
V25	59.84	-	1.73	3.1	-	-	5.64	1.63	2.90	-	2.90	-	1.96	20.3	-
V27	68.89	-	1.12	-	-	-	0.91	1.71	0.96	-	11.0	-	2.01	13.4	-
V29	64.82	-	-	1.36	-	-	4.86	13.8	1.36	-	13.8	-	-	-	-
V31	56.20	-	1.90	1.20	-	-	2.50	0.68	0.88	10.2	9.14	-	2.30	15.0	-
V32	70.51	-	0.78	1.80	-	-	2.70	1.20	0.71	-	3.2	-	-	19.1	-
V33	68.95	-	1.66	2.22	-	-	1.11	1.11	-	0.55	-	2.2	-	22.2	-

Jogipura Sandstones

Detailed study of 12 sandstone samples from Jogipura Formation was undertaken. The sandstones were sampled from thick-bedded, hard and compact, medium sandstones. Detrital mineralogy includes monocrystalline quartz (77.13%), polycrystalline recrystalized metamorphic quartz (0.79%), stretched metamorphic quartz (1.06%), feldspar (1.45%), mica (3.45%), rock fragments (1.34%) and heavy minerals (0.09%) (Table 52). Types of heavy mineral present and their average percentage are as follows: Opaques (92%), tourmaline (3%), biotite (2%), muscovite (1%), zircon (0.5%), rutile (0.5%), kyanite (0.5%) and zoisite (0.5%).

Badalgarh Sandstones

Total 13 sandstone samples from Badalgarh Formation were studied for their mineralogical analysis. Out of 13, 6 samples are from Bhagrain (Table 53) and 7 from Alapuri (Table 54). Average detrital mineralogy for Badalgarh Formation includes monocrystalline quartz (90.68%), polycrystalline recrystalized metamorphic quartz (0.85%), stretched metamorphic quartz (1.14%), feldspar (2.8%), mica (1.36%), rock fragments (1.4%) and heavy minerals (0.49%).

Bayana Sandstones

Total 32 sandstone samples from Bayana Formation are analyzed ; 15 samples from Bayana (Table 55) and 17 samples from Bhimnagar (Table 56) localities. Average detrital mineralogy for Bayana Formation includes monocrystalline quartz (69.82%), polycrystalline recrystalized metamorphic quartz (4.56%), stretched metamorphic quartz (1.41%), feldspar (0.8%), mica (2.32%), rock fragments (0.58%) and heavy minerals (0.63%). Average percentage of heavy minerals is: opaques (84.5%), tourmaline (7%), biotite (3%), muscovite (2%), zircon (0.5%), epidote (0.5%), staurolite (0.5%), rutile (0.5%) and hornblende (0.5%).

Damdama Sandstones

Detailed analysis is done on 13 sandstone samples from Damdama Formation; 6 samples from Kanawar (Table 57) and 7 from Umraind localities (Table 58).

Table 52. Minerological composition of Jogipura Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic	Stretched metamorphic			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
S2	74.14	-	-	-	-	23.38	-	-	1.99	-	0.49	-	-	-	-
S4	96.72	-	-	-	-	3.27	-	-	-	-	-	-	-	-	-
S5	91.30	-	0.86	2.30	0.43	1.53	-	1.30	0.43	0.56	0.86	.43	-	-	-
S8	94.80	-	-	-	-	5.19	-	-	-	-	-	-	-	-	-
S10	92.71	-	0.99	2.31	0.66	0.33	-	0.66	0.66	0.68	-	-	-	-	0.99
S12	61.34	-	-	-	-	1.88	-	-	-	-	1.88	-	-	34.9	-
S14	67.70	-	1.50	-	0.75	2.25	-	-	3.75	3.75	-	-	-	20.3	-
S16	69.12	-	1.92	2.34	-	-	-	1.42	-	-	2.1	-	-	23.1	-
S18	79.18	-	0.99	0.93	-	-	-	2.31	0.67	0.67	1.35	-	-	13.9	-
S20	83.43	-	0.97	2.41	0.56	-	-	2.10	0.68	0.68	0.97	-	-	8.20	-
S22	69.04	-	1.50	1.43	-	-	-	0.58	-	-	0.55	-	-	26.9	-

Table 53. Mineralogical composition of Bhagrain Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized	Stretched			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
Bg1	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bg2	96	-	2	-	-	2	-	-	-	-	-	-	-	-	-
Bg3	96.34	-	-	-	-	2.75	-	-	-	-	0.91	-	-	-	-
Bg5	96.88	-	-	-	-	3.12	-	-	-	-	-	-	-	-	-
Bg7	94.12	-	-	-	-	5.88	-	-	-	-	-	-	-	-	-
Bg9	98	-	-	-	-	1	-	-	-	1	-	-	-	-	-

Table 54. Mineralogical composition of Alapuri Sandstones

Sample. No.	**Monocrystalline quartz (%)**		**Polycrystalline quartz (%)**		**Chert (%)**	**Mica (%)**	**Feldspar (%)**			**Rock Fragments (%)**			**Glass**	**Matrix**	**Heavies (%)**
	Common quartz	Vein quartz	Recrystalized metamorphic	Stretched metamorphic			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
A1	87.35	-	2.81	-	-	2.11	-	-	4.22	2.8	-	0.70	-	-	-
A2	97.16	-	-	-	-	2.83	-	-	-	-	-	-	-	-	-
A4	97.14	-	-	-	-	-	-	-	-	2.85	-	-	-	-	-
A6	99.81	-	-	-	-	0.19	-	-	-	-	-	-	-	-	-
A8	85.00	-	1.36	2.39	1.02	2.73	0.68	2.39	2.39	-	-	1.02	-	-	1.02
A9	85.57	0.74	1.48	3.33	1.11	0.74	-	1.85	1.85	-	-	1.85	-	-	1.48
A11	92.21		0.97	2.28	0.65	0.97	-	0.65	0.65	-	-	0.65	-	-	0.97

Table 55. Mineralogical composition of Bayana Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic quartz	Stretched metamorphic quartz			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
B5	85.73	-	5.71	-	5.14		-	-	-	-	-	1.42	-	2	-
B8	62.62	-	4.65	2.43	-	1.4	-	-	-	-	-	-	-	26.5	2.4
B13	80.31	-	2.77	1	4.48	-	-	-	-	1	0.4	-	-	10	-
B18	64.93	-	3.78	2	-	0.4	-	-	-	0.89	-	-	-	27.2	0.8
B21	77.90	-	2.65	4.88	0.42	1	-	-	-	2.05	1.0	-	0.4	8	1.7
B25	60.10	-	4.57	0.61	3.01	1.4	-	0.6	-	-	-	0.61	-	28.5	0.6
B27	56.36	-	2.41	2.01	2.81	0.6	-	-	0.6	0.60	-	1.42	-	32.5	0.6
B30	60.78	-	1.31	2.26	1.55	4.4	-	-	-	-	-	-	-	28.4	1.3
B32	76.97	-	7.69	1.92	5.76	1.9	-	-	-	1.92	-	3.84	-	-	-
B35	55.94	-	8.84	1.36	2.04	4.0	-	-	-	0.68	-	2.04	-	24.5	0.6
B37	90.49	-	-	-	1.59	6.4	-	-	-	-	0.32	-	-	-	1.2
B40	58.80	-	6.08	1.35	-	8.1	-	-	-	-	-	0.67	-	25	-
B42	43.76	-	4.93	-	2.11	3.5	-	-	-	-	-	0.70	-	45.0	-
B45	89.51	-	6.57	-	1.31	1.3	-	-	-	-	-	1.31	-	-	-
B49	69.47	-	6.50	1.31	1.31	-	-	-	-	-	-	1.31	-	20.0	-

Table 56. Mineralogical composition of Bhimnagar Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic quartz	Stretched. metamorphic quartz			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
BN1	85.74	-	-	1.14	-	0.57	0.57	1.71	3.42	-	-	1.14	-	5.71	-
BN3	73.92	-	2.95	2.95	-	2.46	2.46	5.91	1.47	-	-	1.97	-	5.91	-
BN5	88.78	-	-	-	0.56	1.12	-	3.37	1.68	-	-	0.56	-	3.93	-
BN8	82.69	-	1.65	2.47	-	0.82	1.65	7.02	1.23	-	-	0.41	-	2.06	-
BN10	84.78	-	0.42	2.11	-	1.27	1.27	2.96	0.42	-	-	0.42	-	6.35	-
BN12	78.52	-	3.12	3.15	-	1.17	3.12	2.73	1.17	-	-	1.17	-	5.85	-
BN14	85.41	-	0.42	0.58	-	1.27	2.12	2.12	0.85	-	-	0.85	-	6.38	-
BN16	88.24	-	3.92	0.98	-	-	0.98	-	-	-	-	0.98	-	4.90	-
BN18	70.85	-	10.6	4.42	-	1.76	3.53	4.42	-	-	-	-	-	4.42	-
BN19	70.85	-	2.65	4.42	-	0.88	2.65	8.84	1.76	-	-	1.76	-	6.19	-
BN20	80	-	8	3	-	-	-	-	-	-	-	2	-	7	-
BN22	63.94	-	22.3	-	-	-	0.76	13.0	-	-	-	-	-	-	-
BN24	77.32	-	10.1	4.44	-	-	0.74	6.66	0.74	-	-	-	-	-	-
BN27	75.06	-	5.09	1.07	1.27	-	-	15.6	1.91	-	-	-	-	-	-
BN29	78.74	-	4.95	-	2.47	-	1.60	6.60	0.82	-	-	-	0.82	4.0	-
BN31	83.0	-	5.26	-	1.50	2.90	0.19	6.19	0.21	-	-	-	0.75	-	
BN33	84.1	-	12.1	-	0.73	2.96	-	-	-	-	-	-	-	-	-

Table 57. Mineralogical composition of Kanawar Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic quartz	Stretched metamorphic quartz			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
K1	90.46	-	6.89	-	-	0.86	0.23	-	0.14	-	-	1.12	-	0.3	-
K2	90.19	-	7.3	-	-	1.12	0.10	-	-	-	-	-	-	1.29	-
K4	89.45	-	5.9	0.12	-	2.1	0.12	-	0.12	-	-	0.31	-	1.88	-
K6	95.92	-	2.3	-	-	0.68	0.20	-	-	-	-	-	-	0.9	-
K8	95.35	-	2.6	-	-	0.34	0.18	-	0.13	-	-	0.27	-	1.13	-
K9	92.7	-	5.8	-	-	0.69	0.11	-	-	-	-	-	-	0.7	-

Table 58. Mineralogical composition of Umraind Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic quartz	Stretched. metamorphic quartz			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
U1	92.02	-	3.15	-	-	1.8	0.35	-	0.03	-	-	0.9	-	1.7	-
U3	93.17	-	1.92	-	-	2.03	0.80	-	0.07	-	-	0.11	-	1.9	-
U5	89.45	-	5.9	0.12	-	2.1	0.12	-	0.12	-	-	0.31	-	1.88	-
U6	94.56	-	3.05	-	-	0.9	0.26	-	-	-	-	0.45	-	0.78	-
U8	92.69	-	4.11	-	-	0.41	0.27	-	0.45	-	-	0.2	-	1.87	-
U9	95.34	-	1.51	-	-	0.86	0.64	-	0.32	-	-	0.44	-	0.89	-

Weir Sandstones

Mineralogical analysis was done on 7 sandstone samples from Weir Formation. Detrital mineralogy includes monocrystalline quartz (91.53%), polycrystalline recrystalized quartz (1.78%), stretched metamorphic quartz (2.02%), mica (0.08%), rock fragments (2.36%) and heavy minerals (0.17%) (Table 59).

CLASSIFICATION OF BAYANA BASIN SANDSTONES

For classifying the studied sandstones according to Folk's (1980) scheme, all essential constituents were recalculated to 100 percent ignoring the percentages of clay matrix, all chemically precipitated cements, glauconite, bioclasts, peloids, ooids, heavy minerals and micas. The essential constituents were allotted to one of the three end members:

1. Q - All types of quartz including metaquartzite
2. F - All single feldspar grains plus granite and gneiss fragments
3. R - All other rock fragments (chert, slate, phyllite, schist, volcanics, limestone, sandstones, shale).

The average composition of framework grains of the sandstones of Bayana Basin is Q – 93.28 %, F – 3.24 % and R – 3.48 %

All the samples of the studied sandstones are plotted near the Q pole, in the quartzarenite field. The individual formation wise study indicates that most of the samples fall in quartzarenite field followed by sublitharenite, feldspathic litharenite, arkose and subarkose fields (Figure 38).

FACTORS CONTROLLING DETRITAL MINEROLOGY

Distance of transport is one of the factors, which controls the composition at the time of deposition. The processes of mechanical breakdown, abrasion, hydrodynamic sorting during transportation etc. result in compositional maturation

Table 59. Mineralogical composition of Weir Sandstones

Sample. No.	Monocrystalline quartz (%)		Polycrystalline quartz (%)		Chert (%)	Mica (%)	Feldspar (%)			Rock Fragments (%)			Glass	Matrix	Heavies (%)
	Common quartz	Vein quartz	Recrystalized metamorphic quartz	Stretched metamorphic quartz			Plagioclase	Orthoclase	Microcline	Sedimentary	Volcanic	Metamorphic			
W1	84.55	-	-	2.08	-	1.04	-	-	-	-	-	8.33	-	4.0	-
W2	87.95	-	1.11	4.44	-	2.08	-	-	-	1.1	-	1.1	-	2.22	-
W3	89.86	-	3.12	3.9	-	1.56	-	-	-	-	-	1.56	-	-	-
W4	86.92	-	4.54	-	-	4.0	-	-	-	-	-	4.54	-	-	-
W5	96.25	-	1.25	2.5	-	-	-	-	-	-	-	-	-	-	-
W6	98.88	-	-	-	-	1.11	-	-	-	-	-	-	-	-	-
W7	95.00	-	2.5	1.25	-	1.25	-	-	-	--	-	-	-	-	-

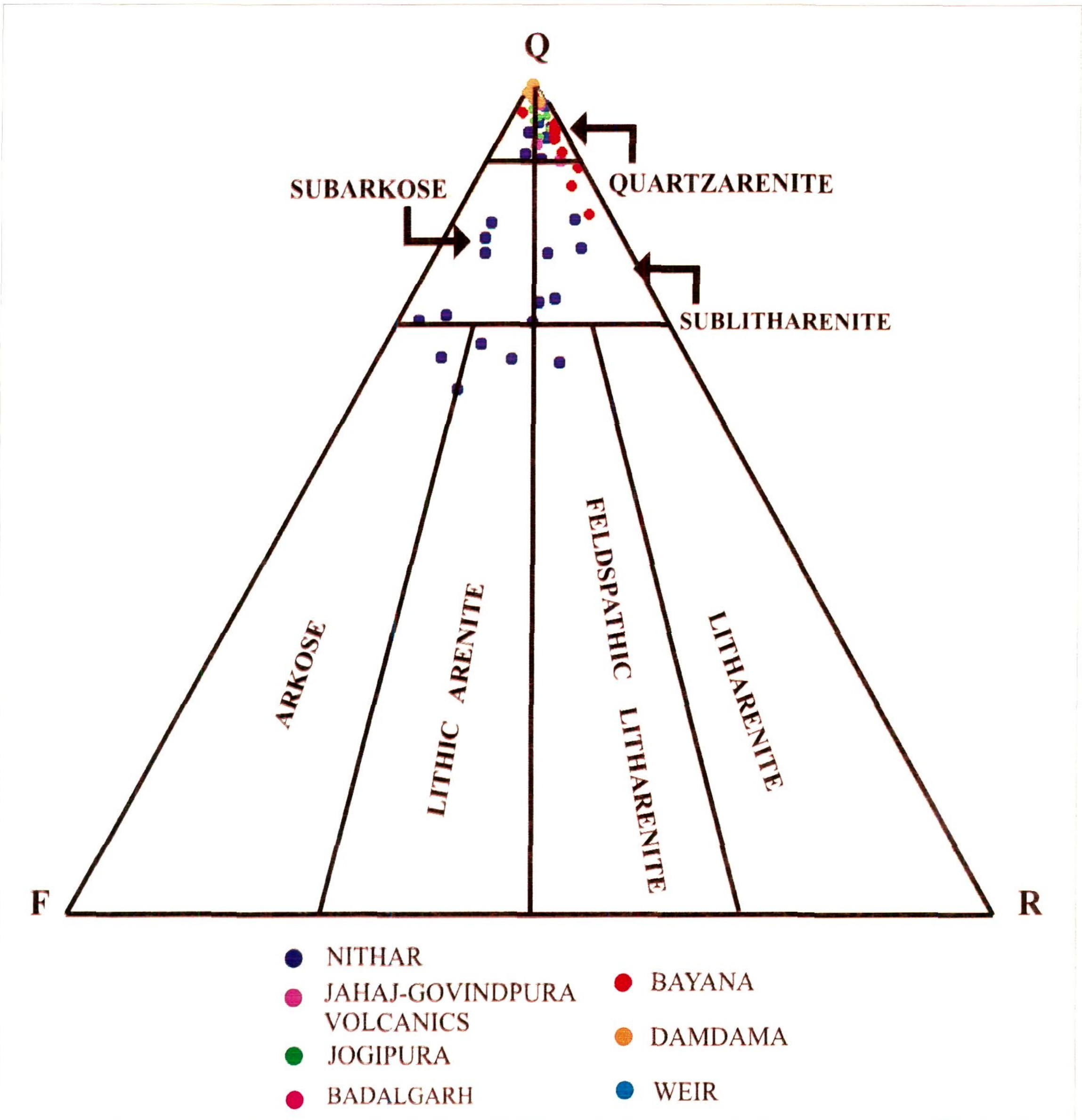

Figure 38. Classification of sandstones of Bayana Basin, according to Folk (1980).

of detritus into more quartzose detrital mode. The percentages of rock fragments, feldspar and polycrystalline quartz, all decrease with increase in transport distance and / or reworking (Blatt, 1967; Franzinelli and Potter, 1983; Lucchi, 1985). Large stream show few or no change in mineral composition even during prolonged transport and whatever feeble changes occur are not the result of differential abrasion (Russel, 1939). There appears to be only a small loss of feldspar relative to quartz and no appreciable loss of feldspar in high gradient gravel carrying streams. The detrital grains of Bayana Basin sandstones are in the sand size range and derived from only 100 km distance from Dausa uplift and Rajputana craton (Singh,1985). Due to presence of small amount of feldspar and rock fragments in the studied sandstone, prolonged reworking and presence of high gradient stream is quite likely within the basin. However this premise doesn't stand to scrutiny because rock fragment that could have been destroyed more easily are more common than the feldspars. Therefore, some factor other than transportation was responsible for the occurrence of small amount of feldspars in the studied sandstones.

DIAGENETIC MODIFICATION

The detrital composition of sands may be altered by diagenetic processes, which must be taken into consideration, while making provenance interpretation (McBride, 1985). The diagenetic modifications include loss of detrital framework grains by dissolution, alteration of grains by replacement or recrystallization, and the loss of identity of certain ductile grains during compaction, which give rise to pseudomatrix.

The presence of weathered feldspar grains as well as oversize pores indicates dissolution of detrital grains in the studied sandstones. The replacement of quartz grains by iron and carbonate in some thin sections suggest slight modification of the composition of the sandstones. The study of grain contacts of the Bayana Basin sandstones indicates that the sandstones are subjected to compaction during burial and their original texture and fabric slightly modified by the process of compaction.

SOURCE ROCK COMPOSITION

Although the detrital mineralogy of the Bayana Basin sandstones appears to have been modified by transportation, it has potential to reflect the nature of source rocks. The lithological composition of the rocks in the source area may be the most potent and dominating agent that affects the final sandstone composition (Krynine, 1948). A study of light and heavy mineral fractions of the sandstones is important in interpreting the provenance character. Among the light minerals quartz is the dominant constituent and can be a good indicator of provenance. Krynine (1948) used quartz as guide to the provenance. His approach was based on grain shape, type of inclusion and extinctions (undulatory or non-undulatory). Applying this criterion, he discriminated igneous plutonic and metamorphic origins of monocrystalline quartz. But these criteria are usually difficult to apply (Bokman, 1952).

Usefulness of polycrystalline or composite quartz in this respect has been emphasized by many authors (Voll, 1960; Blatt and Christie, 1963, Basu, 1985). Those showing two distinctly different sizes of crystals within a single polycrystalline grain are diagnostic of metamorphic quartz. A high ratio of polycrystalline quartz to total quartz also suggests a metamorphic source.

Basu et al. (1975) used the criteria of undulosity and polycrystallinity in his studies and concluded that higher proportion of moderately to strongly undulose monocrystalline quartz grain (undulosity >5) and higher proportion of polycrystalline quartz in medium sand size is characteristics of metamorphic source. Plutonic rocks tend to provide non-undulose or weakly undulose (undulosity ≤ 5) monocrystalline quartz and polycrystalline quartz grain with only two or three subgrains.

Feldspars, the second most common mineral in sandstones, make them suitable as provenance indicators. Being unstable, feldspar may, however, be selectively modified or removed from the detritus during weathering, transportation and diagenesis, resulting in decrease of their effectiveness as provenance indicator. They can be derived from different sources and show variation in their chemical composition and physical properties which have genetic implications. The most useful properties are chemical compaction, zoning, twinning and structural state.

Felspars are very sensitive to weathering process which requires suitable climate as well as proper length of time which in itself is determined by relief. The presence or absence of feldspars depends on the process of erosion and decomposition operating there. Therefore, detrital feldspar is an index of both climatic vigour and tectonism.

Bayana Basin sandstones contain common varieties of mica, like muscovite and biotite. These may be derived from metamorphic, plutonic and rarely volcanic rocks. In general, presence of mica in sediments is suggestive of metamorphic provenance.

Rock fragments are among the most informative of all the detrital components. Sandstones commonly contain rock particles of volcanicolithic, sedimentary, and metamorphic origin (shale, phyllite, siltstone, schists, quartzite, gneiss etc., rarely granite fragments). They carry their own evidence of provenance (Bogg, 1968).

Heavy minerals provide exceptionally useful clue to the nature of source rocks. Like lighter fractions, they too are influenced by weathering, transportation and diagenesis. Important contributions in this field are those of Krynine (1946); Vintage (1957); Faupl and Wagreich (1992) and Faupl et al. (2002).

The sandstones of Bayana Basin contain quartz, both of igneous and metamorphic origins as well as feldspar, rock fragments, micas and heavy minerals. The most abundant quartz is common quartz. It is mainly derived from granitic batholiths or granite-gneisses. The recrystalized quartz indicates an origin from metaquartzites, highly metamorphosed granite and gneissic rocks. The stretched quartz was probably, derived from granites, schists or quartz veins.

To evaluate the relative importance of quartz grain types (Table 60) for determining the provenance of the Bayana Basin sandstones, a combined plot of

Table 60. Types of quartz grain in the sandstones of Bayana Basin

Sample no.	**Monocrystalline quartz**		**Polycrystalline quartz**	
	Non-undulatory	**Undulatory**	**2-3 crystals**	**> 3 crystals**
NITHAR FORMATION				
N4	83	3	7	7
N6	80	2	13	10
N9	79	2	7	21
N12	96	-	6	6
N14	80	1	9	10

N17	72	4	6	18
N19	90	2	-	8
N21	83	6	2	9
N22	90	-	3	7
N23	90	3	2	5
JGV FORMATION				
V1	90	10	-	-
V3	78	22	-	-
V5	82	18	-	-
V7	81	19	-	-
V9	84	16	-	-
V11	82	18	-	-
V12	90	10	-	-
V14	84	16	-	-
V15	75	25	-	-
V17	88	22	-	-
V19	87	13	-	-
V21	66	34	-	-
V23	81	19	-	-
V25	71	29	-	-
V27	72	28	-	-
V29	96	4	-	-
V31	70	30	-	-
V32	65	34	-	-
V33	82	18	-	-
JOGIPURA FORMATION				
S2	85	4	2	9
S3	94	2	-	4
S4	91	-	3	6
S5	91	3	1	5
S8	89	3	1	7
S10	56	5	9	30
S12	68	3	10	19
S14	64	3	13	20
S16	76	3	-	21
S18	78	5	4	13
S20	66	-	-	34
S22	76	6	10	21
BADALGARH FORMATION				
Bg1	82	8	4	6
Bg2	96	-	-	4
Bg3	80	6	7	7
Bg5	96	-	-	4
Bg7	94	-	-	6
Bg9	98	-	-	2
A1	80	7	3	10
A2	97	-	-	3
A4	95	-	-	5
A6	98	-	-	2

A8	84	-	-	6
A9	77	4	3	6
A11	89	2	2	8
BAYANA FORMATION				
B5	81	4	7	8
B8	56	6	10	28
B13	71	8	6	13
B18	61	3	21	25
B21	73	5	8	14
B25	51	4	15	30
BN10	80	4	6	10
BN12	74	4	6	16
BN14	79	6	9	6
BN16	88	-	-	12
BN18	62	8	12	18
BN19	70	-	10	20
BN20	80	-	-	20
DAMDAMA FORMATION				
K1	87	3	4	6
K2	88	2	2	8
K4	86	3	2	9
K6	90	5	-	5
K8	92	3	-	5
K9	86	6	5	3
WEIR FORMATION				
W1	82	3	6	9
W2	86	2	4	8
W3	85	4	3	8
W4	83	4	3	10
W5	96	-	-	4
W6	98	-	-	2
W7	92	2	1	5

polycrystalline (composite grains) quartz versus undulatory (strained) to non-undulatory (unstrained) monocrystalline quartz is prepared (Figure 39), following the technique of provenance discrimination diagram of Basu et al. (1975). Most of the data points fall in the plutonic area and rest of them fall in the upper metamorphic zone. The plot yields consistent results that indicate a source area containing largely plutonic and middle to high rank metamorphic rocks, which represent the exposed roots of magmatic arcs or older crystalline basement in the area (Dickinson and Suczek, 1979).

Micas present in the sandstones of Bayana Basin comprise mainly muscovite and a few biotite flakes derived, probably from granites, pegmatites or schists. The

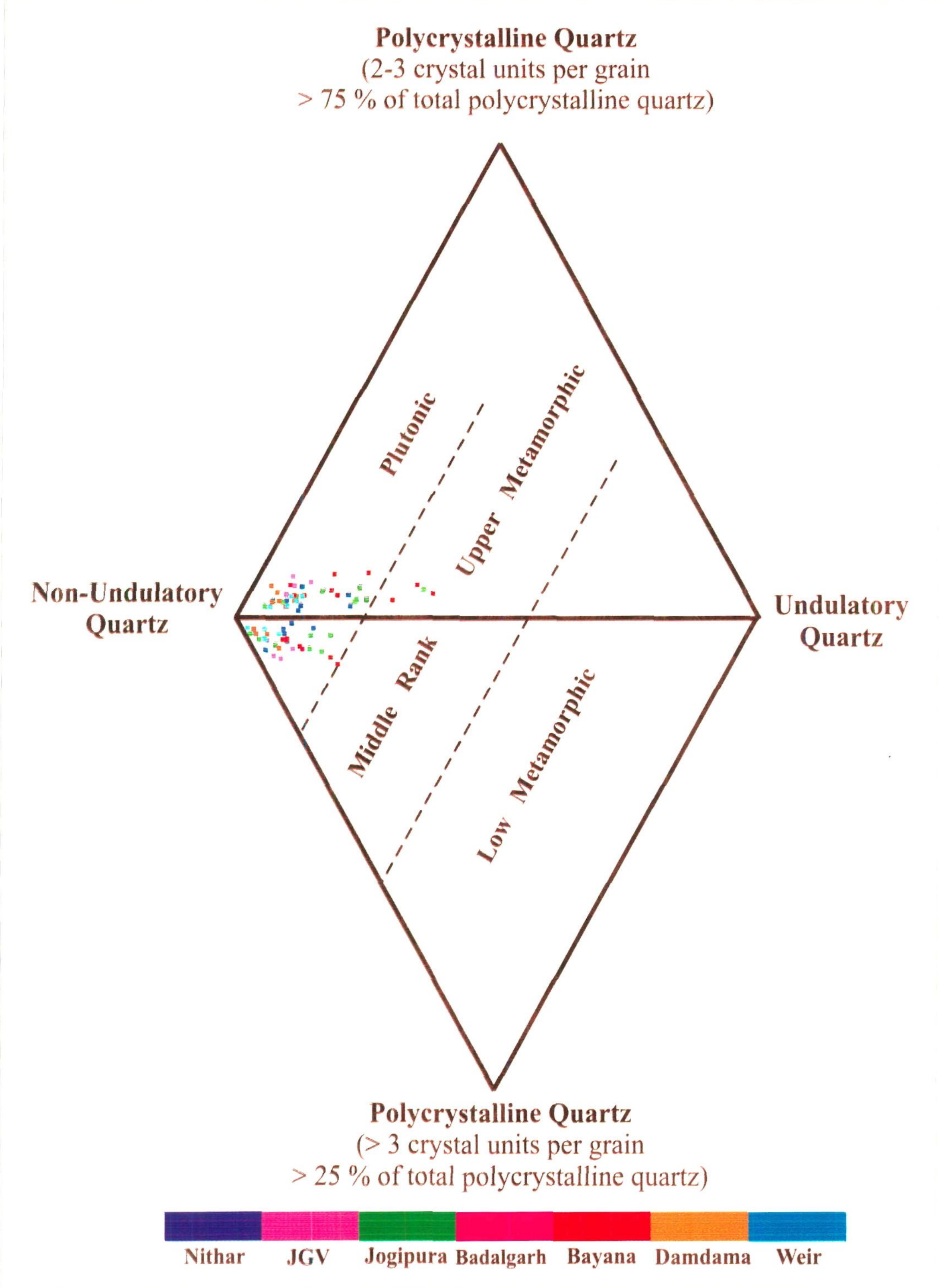

Figure 39. Classification of Bayana Sandstones according to Basu et al (1975)

presence of abundant opaque grains in these sandstones reflects their derivation from metamorphic rocks. The suite of heavy minerals including biotite, zircon, tourmaline, and rutile indicates igneous (plutonic) source for these sediments. On the other hand the suite of heavy minerals including epidote, garnet and staurolite reflects metamorphic source for these sediments. (Morton 1985; Wanas and Abdel-Maguid 2006). The suite of heavy minerals including rounded grains of rutile, tourmaline and zircon is indicative of the reworked source for these sandstones. Presence of alkali feldspar indicates their source as both plutonic and metamorphic rocks but abundant microcline feldspar indicates granitic as well as pegmatitic source. From the above discussion, interpretation can be drawn that sediments of Bayana Basin sandstones were derived from a variety of source rocks (mixed provenance).

The paleocurrent pattern and palaeogeographic setup for the Bayana Basin indicates a provenance area in southwest, identified as Dausa uplift and Rajputana craton comprising granitic gneissic basement rocks and metamorphosed supracrustal located within 100 km of the basin.

Petrofacies

CHAPTER - VI

PETROFACIES

The Sandstones petrography and its relationship to tectonic setting is one of the subjects of extensive research in geology. In sedimentary petrology, the term *'provenire'*, meaning to 'originate' is used for the study of the compositional and textural properties of sediments from the initial source area. Thus the intent of sedimentary provenance studies is to reconstruct and to interpret the history of sediment from the initial erosion of parent rocks to the final burial of their detritus, i.e., to unravel the line of descent or lineage of the sediment under investigation (Weltje and Eynatten, 2004). Petrofacies, as defined by Dickinson and Rich (1972), implies detrital composition of sandstone and its significance to regional tectonic framework and contemporary tectonic activity in the source and depositional areas. The relationship between plate-tectonics and sandstone composition has been the subject of intensive research and discussion over the last three decades.

Clastic sediments are made up of two types of materials; detrital grains, which are the residues of weathered parent rocks and fine-grained sediments, which are composed of clay minerals from weathered unstable minerals. Chemical alteration and mechanical breakdown of source rocks, modifications by recycling, transport, mixing, deposition, diagenesis etc., control the compositional and textural characteristics of the detrital grains. Naturally final properties of the sediments, therefore, essentially bear the signature of the parent lithology along with the entire process of modification that the sediments had gone through. Fine-grained sediments undergo mechanical/chemical modification and decompose into individual mineral grains. Therefore they often fail to give information about pre-modification processes. But detrital grains are capable of preserving that information which can be analyzed to estimate their source and the initial tectonic setting. Therefore, source and tectonic setting of sandstones can be determined by detrital modes (framework mineral composition). The process was first proposed by Crook (1974) which was later modified by Dickinson (1983, 1985) and others.

The relationship between plate-tectonics and sandstone composition has been the subject of intensive research and discussion over the last three decades. Many studies have pointed to an intimate relationship between detrital sand composition and tectonic setting (Crook,1974; Ingersoll, 1978; Potter, 1978; Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Dickinson and Valloni,1980; Schwab,1981; Valloni and Mezzardi,1984; Bhatia, 1985; Dickinson,1985; Bhatia and Crook, 1986; Schwab, 1986; Garzanti, 1986; DeCelles and Hertel, 1989; Akhtar and Ahmad, 1992; Cox and Lowe, 1995; Arribus et al., 2003; Ahmad et al., 2006; Ahmad and Bhat, 2006)

The proportion of detrital framework grains plotted on triangular diagram provides effective discrimination of a variety of plate-tectonic settings and have been used as a powerful tool for determining the origin and tectonic reconstruction of terrigenous deposits (Graham et al., 1976 ; Dickinson, 1985). But, sometimes, correlation between tectonic setting and sandstone petrofacies does not hold good due to other factors that influence the detrital mineralogy of sandstones. (Ingersoll, 1990). Climate and relief play most important role in this regard. The tropical warm and humid climate aided by low relief that result in intense chemical weathering, is the most effective agent of modification of original detrital composition (Basu, 1985 ; Girty, 1991). Other modifying agents are sediment transport across tectonic boundaries and their deposition in tectonically alien basin (Velbel, 1985 ; Lucchi, 1985), varying tectonic style at provenance and mixing from two sources (Ingersoll, 1990), sediment recycling (Cox and Lowe, 1995), sediment reworking in depositional environment (Espejo and Gamudi, 1994) and diagenesis (McBride, 1985). Hence, it is necessary to synthesize the petrofacies for a logical identification of tectono-provenance.

CLASSIFICATION BASED ON DICKINSON'S (1985) SCHEME

In the present study, the detrital minerals of Bayana Basin sandstones were studied for the purpose of interpreting their provenance and plate tectonic setting. Dickinson's (1985) classification scheme for sandstone has been employed for this purpose. Dickinson (1985) classified sandstones on the basis of their characteristic petrofacies, which is primarily controlled by the tectonic setting of their provenance (Table 61). However, secondary factors (relief, climate, transport mechanism, depositional environment, and diagenesis) can also play important role in determining the sandstone composition. He used detrital modes of 88 sandstone suites, which reflect different tectonic settings of provenance terrains, and grouped the provenance related to continental sources, into four major types:

Stable cratons,

Basement uplifts,

Magmatic arcs and

Recycled orogens.

In the present study, the detrital modes were recalculated to 100 percent as the sum of Qt, Qm, Qp, F, P, K, L, Lt, Lv and Ls (Table 62). The percentages of heavy minerals are ignored as they are highly variable as a result of variable response to hydrodynamic and geochemical influences.

In this study four triangular diagrams, Qt-F-L, Qm-F-Lt, Qp-Lv-Ls and Qm-P-K were used. Both Qt-F-L and Qm-F-Lt plots show full grain populations, but with different emphasis. In Qt-F-L plot, where all quartzose grains are plotted together, the emphasis is on grain stability, and thus on weathering, provenance relief, and transport mechanism as well as source rock; while in Qm-F-Lt, where all lithic fragments are plotted together, the emphasis is shifted towards the grain size of source rock, because fine-grained rocks yield more lithic fragments in the sand-size range. The Qp-Lv-Ls and Qm-P-K plots show only partial grain populations, but reveal the character of polycrystalline and monocrystalline components of the framework, respectively.

Sandstones from different tectonic settings have characteristic detrital components and characteristic chemistry (Crook, 1974; Dickinson and Suczek, 1979; Valloni and Maynard, 1981; Dickinson et al., 1983) (Bhatia, 1983; Roser and Korsch, 1986; Kroonenberg, 1994). The determination of the tectonic setting of sandstones using the framework mineral composition (detrital modes) was first proposed by Crook (1974), and has since undergone considerable refinement (e.g.

Dickinson and Suczek, 1979; Dickinson et al., 1983). The study revealed that monocrystalline quartz (Qm) is the dominant mode of the sandstones. Its percentage ranges from 58.51 % to 96.7 %, average at 84.68 %. Polycrystalline quartz (Qp) includes both recrystallized quartz and stratched metamorphic quartz. Polycrystalline recrystallized quartz ranges from 0.3 % to 5.54 % and stretched metamorphic quartz ranges from 0.1% to 2.10 % of the detrital fraction. The feldspars (F) occur in small amounts in the Delhi basin sandstones and includes plagioclase, orthoclase and microcline. The average percentage of feldspar is 3.98 %. Rock fragments include shale, siltstone, chert, schist, gneiss, quartzite and volcanic lithic. Their percentages range from 0.36 % to 10.16% .

Most of the samples of the Bayana Basin sandstones lay in continental block provenance field in Qt- F- L plot (Figure 40) suggesting contribution from the craton interior with basement uplift. Rest of the samples fall in the recycled orogen provenance which suggest their derivation from metasedimentary and sedimentary rocks that were originally deposited along former passive continental margins (Dickinson and Suczek, 1979; Dickinson 1985). The Qm-F-Lt (Figure 41) plot showed that the samples fall in continental block provenance with little contribution from the recycled orogen provenance. In the Qm-P-k (Figure 43) diagram, the data lie in the continental block provenance reflecting maturity of sediments and stability of source area. The Qp – Lv – Ls plot, (Figure 42) which is based on rock fragments population reveals the polymineralic component of source region and gives a more resolved picture about the tectonic elements.

Table 61. Classification and symbols of grain types (after Dickinson, 1985)

A. Quartzose Grain (Qt = Qm + Qp)

Qt = Total quartz grain

Qm = Monocrystalline quartz

Qp = Polycrystalline quartz

B. Feldspar grain (F = P + K)

F = Total feldspar grains

P = Plagioclase grains

K = K-feldspar grains

C. Unstable lithic fragments (L = Lv + Ls)

L = Total unstable lithic fragments

Lv = Volcanic/metavolcanic lithic fragments.

Ls = Sedimentary/metasedimentary fragments.

D. Total lithic fragments : (Lt = L + Qp)

Lc = Extrabasinal detrital lime clast (not included in L or Lt)

Table 62. Percentages of framework modes of the sandstones of Bayana Basin (Based on Dickinson's 1985 classification).

Sample No.	Qt	F	L	Qm	F	Lt	Qp	Lv	Ls	Qm	P	k
NITHAR FORMATION												
N4	96.7	3	0.3	95	3	2	100	-	-	96.4	-	3.6
N6	96	4	-	94	4	2	100	-	-	96.1	-	3.9
N9	94.1	5	0.9	93	5	2.02	100	-	-	94.9	-	5.1
N12	93.9	5.05	1.05	89.9	5.05	5.05	100	-	-	94.8	0.85	4.35
N14	96	4	-	93	4	3	100	-	-	95.8	0.41	3.79
N17	93.9	5.05	1.05	91.84	5.10	3.06	100	-	-	94.65	-	5.35
N19	95	5	-	93	5	2	100	-	-	93.75	6.25	
N21	94.75	3.15	2.10	92.72	3.12	4.16	100	-	-	97.1	0.83	2.07
N22	92.93	5.05	2.02	90.9	5.05	4.05	100	-	-	94.5	-	5.44
N23	95	3	2	93	3	4	100	-	-	97.2	-	2.70
JAHAJ-GOVINDPURA VOLCANIC FORMATION												
V1	62.73	10.5	26.77	60.66	10.69	28.35	4.69	50.83	44.47	85.07	9.78	5.14
V3	66.56	6.91	26.52	63.14	6.91	29.94	11.43	56.14	32.42	90.12	6.58	3.29
V5	70.85	14.64	14.51	66.0	14.74	19.25	23.78	50	26.22	81.75	14.32	3.92
V7	71.15	2.18	26.67	64.60	2.39	33.00	11.5	63.9	24.6	96.4	2.16	1.43
V9	79.81	15.48	4.70	71.74	15.72	12.53	61.82	38.18	-	82.01	15.32	2.67
V11	79.21	11.97	8.82	71.70	12.15	16.14	44.59	55.40	-	85.50	11.95	2.54
V12	79.21	5.20	15.58	75.52	5.31	19.16	6.39	78.72	14.88	93.42	2.52	4.05
V14	73.78	15.60	10.62	69.22	15.58	15.2	28.76	28.09	43.14	81.47	11.75	6.77
V15	66.48	14.59	18.93	56.41	14.59	29.00	34.66	30.19	35.15	79.45	15.59	4.86
V17	91.06	3.72	5.21	89.20	3.75	7.04	25.50	10.73	63.77	95.96	1.49	2.54
V19	73.24	14.18	12.57	71.18	14.18	14.63	14.08	83.29	2.62	83.38	12.49	4.12
V21	68.21	10.48	21.31	66.71	10.48	22.80	6.57	44.93	48.49	86.41	6.20	7.38
V23	81	4.35	14.64	80.60	4.44	14.95	-	69	31	94.77	1.68	3.55

V25	83.17	13.09	3.74	76.95	13.09	9.95	62.48	37.51	-	85.46	8.06	6.47
V27	82.74	4.23	13.02	81.42	4.23	14.34	9.24	90.75	-	95.05	1.25	3.69
V29	66.11	20.06	13.83	64.74	20.06	15.19	8.97	91.02	-	76.34	5.74	17.91
V31	71.63	4.91	23.46	67.88	4.91	27.20	13.79	40.67	45.54	93.24	4.15	2.60
V32	90.34	5.70	3.95	87.15	5.70	7.14	44.63	55.36	-	93.86	3.59	2.54
V33	93.55	2.87	3.57	88.27	2.93	8.79	87.58	-	12.41	96.78	1.6	1.62
SITAKUND (JOGIPURA FORMATION)												
S2	94.05	4.76	1.18	94.06	4.76	1.17	-	-	-	95.18	-	4.81
S4	100	--	-	100	--	--	100	-	-	100	-	-
S5	96.36	1.75	1.88	92.65	1.75	5.59	76.14	10.36	13.49	98.14	-	1.85
S8	100	-	-	100	-	-	100	-	-	100	-	-
S10	98.05	1.27	0.67	94.66	1.28	4.05	83.33	-	16.66	98.59	-	1.40
S12	97.02	-	2.97	97.02	-	2.97	-	-	-	100	-	-
S14	95.15	-	4.84	93.15	-	6.84	28.57	-	71.42	100	-	-
S16	92.91	4.35	2.73	88.43	4.40	7.17	100	-	-	95.24	-	4.75
S18	94.96	2.68	2.35	92.73	2.68	4.58	74.13	-	25.86	-	-	-
S20	95.32	2.87	1.80	91.59	2.89	5.51	83.25	-	16.74	97.18	-	2.81
S22	95.58	3.66	0.75	91.57	3.66	4.76	100	-	-	96.14	-	3.85
BHAGRAIN (BADALGARH FORMATION)												
Bg1	100	-	-	100	-	-	-	-	-	100	-	-
Bg2	100	-	-	97.9	-	2.1	100	-	-	100	-	-
Bg3	99.06	-	0.93	99.06	-	0.93	-	-	-	100	-	-
Bg5	100	-	-	100	-	-	-	-	-	100	-	-
Bg7	100	-	-	100	-	-	-	-	-	100	-	-
Bg9	100	-	-	100	-	-	-	-	100	100	-	-
ALAPURI (BADALGARH FORMATION)												
A1	92.11	4.31	3.57	89.23	4.33	6.44	50.08	-	49.91	95.39	-	4.60
A2	100	-	-	100	-	-	-	-	-	100	-	-
A4	97.1	-	2.86	-	-	-	-	-	100	100	-	-

	4											
A6	100	--	-	-	-	-	-	-	-	100	-	-
A8	93.26	5.67	1.06	89.24	5.73	5.02	100	-	-	93.95	0.75	5.29
A9	90.15	7.94	1.90	85.06	8.03	6.90	100	-	-	91.36	-	8.63
A11	97.09	2.31	0.60	93.66	2.33	4.00	100	-	-	97.58	-	2.42
BAYANA FORMATION												
B5	98.55	-	1.44	92.32	-	7.67	100	-	-	100	-	-
B8	100	-	-	89.81	-	10.18	100	-	-	100	-	-
B13	98.43	-	1.56	93.91	-	6.08	72.92	7.73	19.34	100	-	-
B21	96.60	-	3.39	88.16	-	11.83	71.17	9.45	19.37	100	-	-
B25	98.13	0.92	0.94	89.65	0.97	9.37	100	-	-	98.92	-	1.07
B27	96.04	0.90	3.05	88.89	0.94	10.16	88.04	-	11.95	98.94	-	1.05
B30	100	-	-	94.52	-	5.47	100	-	-	100	-	-
B32	94.12	-	5.87	83.34	-	16.65	83.34	-	16.65	100	-	-
B35	96.15	-	3.84	81.19	-	18.80	93.75	-	6.25	100	-	-
B37	99.65	-	0.34	99.64	-	0.35	-	100	-	100	-	-
B40	98.99	-	1.00	87.88	-	12.11	100	-	-	100	-	-
B42	98.63	-	1.36	88.60	-	11.39	100	-	-	100	-	-
B45	98.67	-	1.32	91.90	-	8.09	100	-	-	100	-	-
B49	98.36	-	1.63	88.39	-	11.60	100	-	-	100	-	-
BHIMNAGAR (BAYANA FORMATION)												
BN1	92.69	6.08	1.22	91.48	6.08	2.43	100	-	-	93.76	0.62	5.61
BN3	87.10	10.74	2.15	80.66	10.74	8.59	100	-	-	88.24	2.93	8.82
BN5	94.08	5.32	0.59	89.29	5.35	5.35	100	-	-	94.34	-	5.65
BN8	89.37	10.20	0.42	85.12	10.20	4.67	100	-	-	89.29	1.78	8.92
BN10	94.50	5.03	0.47	91.76	5.03	3.20	100	-	-	94.79	1.42	4.46

BN12	91.18	7.55	1.26	84.05	7.55	8.39	100	-	-	91.75	3.66	4.58
BN14	93.56	5.51	0.92	92.18	5.51	2.30	100	-	-	94.35	2.35	3.29
BN16	97.93	1.03	1.03	92.78	1.03	6.18	100	-	-	98.90	1.09	-
BN18	91.51	8.49	-	75.46	8.48	16.05	100	-	-	89.89	4.48	5.62
BN19	83.83	14.26	1.90	76.22	14.26	9.51	100	-	-	84.23	3.15	12.61
BN20	81.98	-	18.01	72	-	28	100	-	-	100	-	-
BN22	86.16	13.83	-	63.84	13.83	22.33	100	-	-	88.66	1.05	10.28
BN24	91.84	8.15	-	77.05	8.14	14.81	100	-	-	90.44	0.86	8.68
BN27	82.48	17.52	-	76.01	17.74	6.24	100	-	-	81.07	-	18.92
BN29	90.89	9.10	-	85.53	9.33	5.13	100	-	-	90.15	1.74	8.10
BN31	96.33	3.66	-	90.19	3.72	6.08	100	-	-	96.03	0.23	3.73
BN33	100	-	-	87.36	-	12.63	100	-	-	100	-	-
UMRAIND (DAMDAMA FORMATION)												
U1	97.24	2.19	0.57	88.11	2.19	9.69	100	-	-	97.56	1.08	1.35
U3	98.60	1.39	-	89.83	1.39	8.78	100	-	-	98.46	-	1.53
U5	98.44	1.55	-	95.03	1.55	3.41	100	-	-	98.39	0.58	1.02
U6	98.91	1.08	-	94.03	1.08	4.88	100	-	-	98.86	-	1.13
U8	98.39	0.21	1.39	93.52	0.21	6.26	100	-	-	99.77	-	0.22
U9	97.94	1.06	1	89.63	1.29	9.07	100	-	-	98.57	-	1.42
U10	99.23	0.76	-	91.22	0.76	8.01	100	-	-	99.16	-	0.83
KANAWAR (DAMDAMA FORMATION)												
K1	98.49	0.37	1.13	91.52	0.37	8.10	100	-	-	99.59	0.25	0.15
K2	99.89	0.10	-	92.41	0.10	7.48	100	-	-	99.88	0.11	-
K4	99.42	0.24	0.33	93.15	0.24	6.60	100	-	-	99.73	0.13	0.13
K6	99.79	0.20	-	97.47	0.20	2.33	100	-	-	99.79	0.20	-
K8	99.4	0.31	0.27	99.1	0.32	0.55	100	-	-	99.6	0.18	0.14

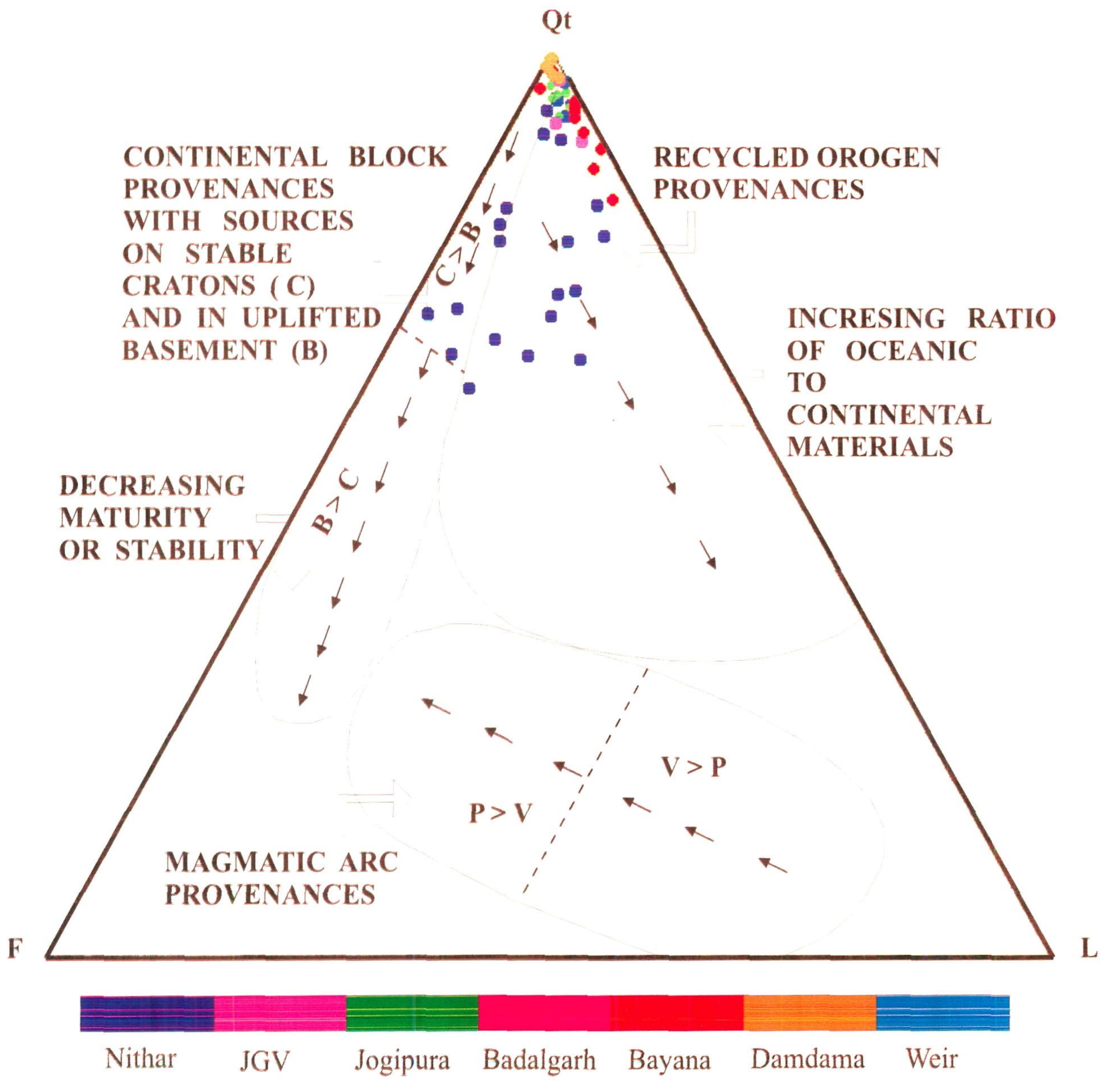

Figure 40. Qt-F-L plot of the sandstones of Bayana Basin, according to Dickinson (1985)

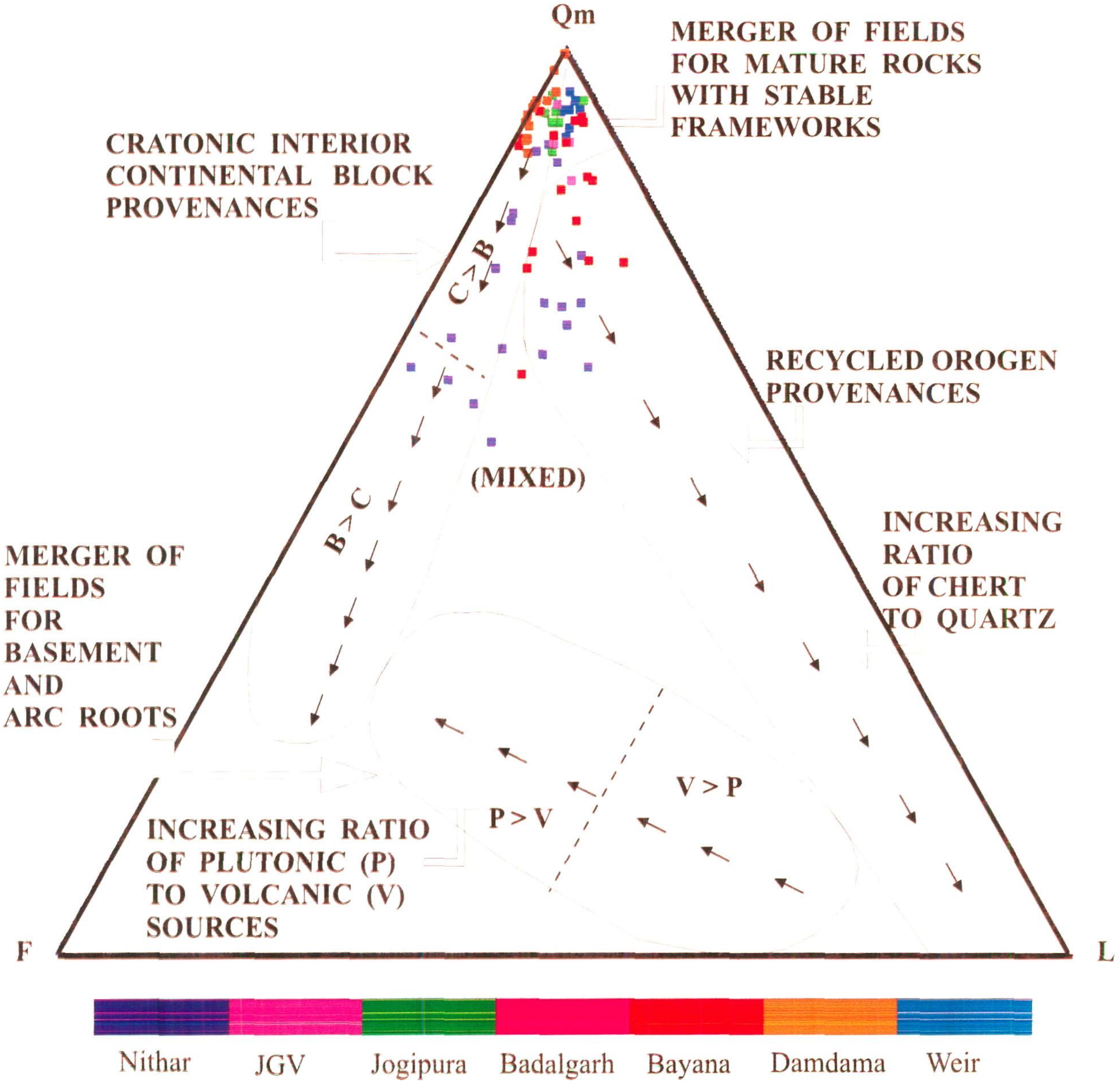

Figure 41. Qm-F-Lt plot of the sandstones of Bayana Basin, according to Dickinson (1985)

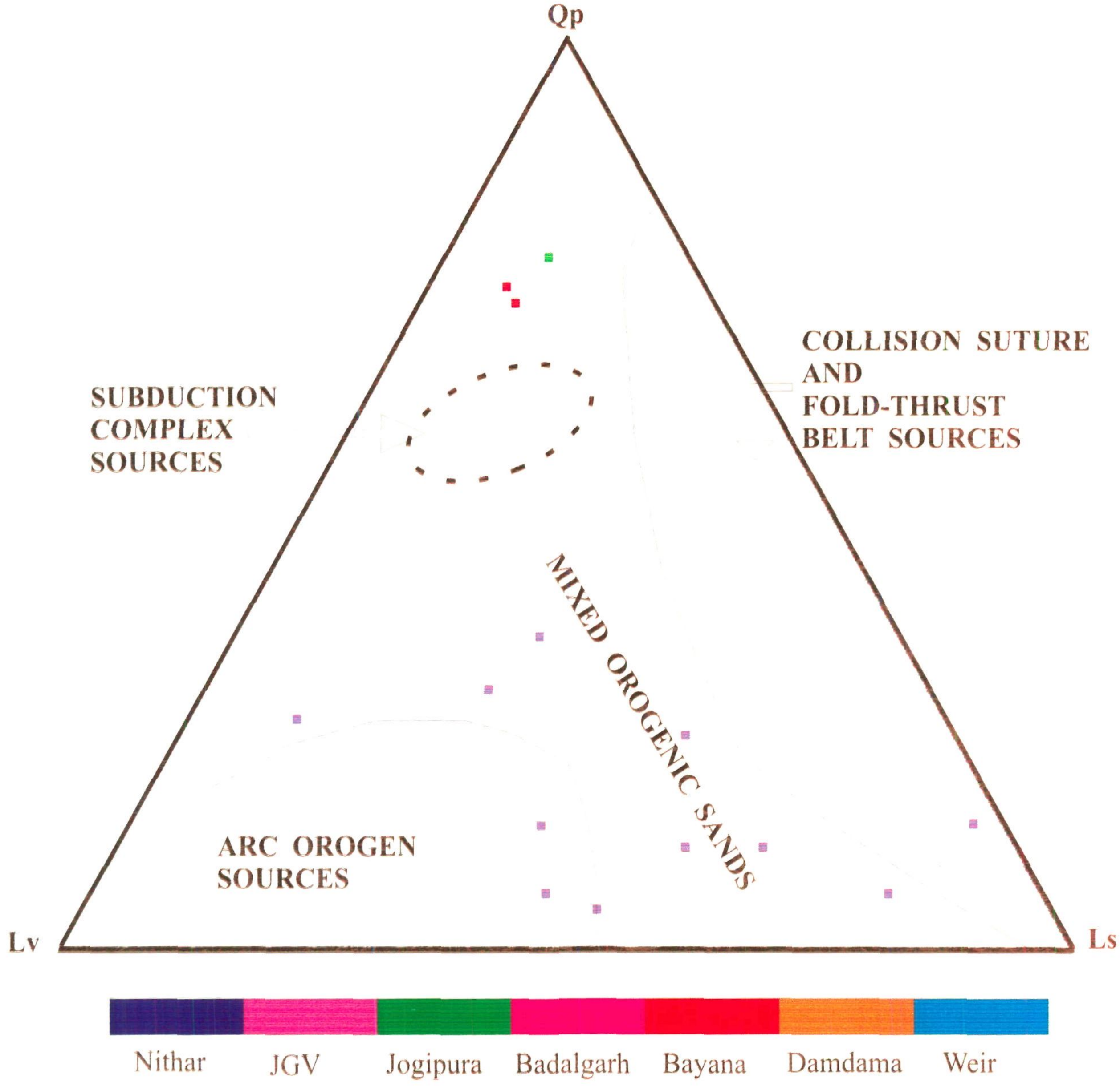

Figure 42. Qp-Lv-Ls plot of the sandstones of Bayana Basin, according to Dickinson (1985)

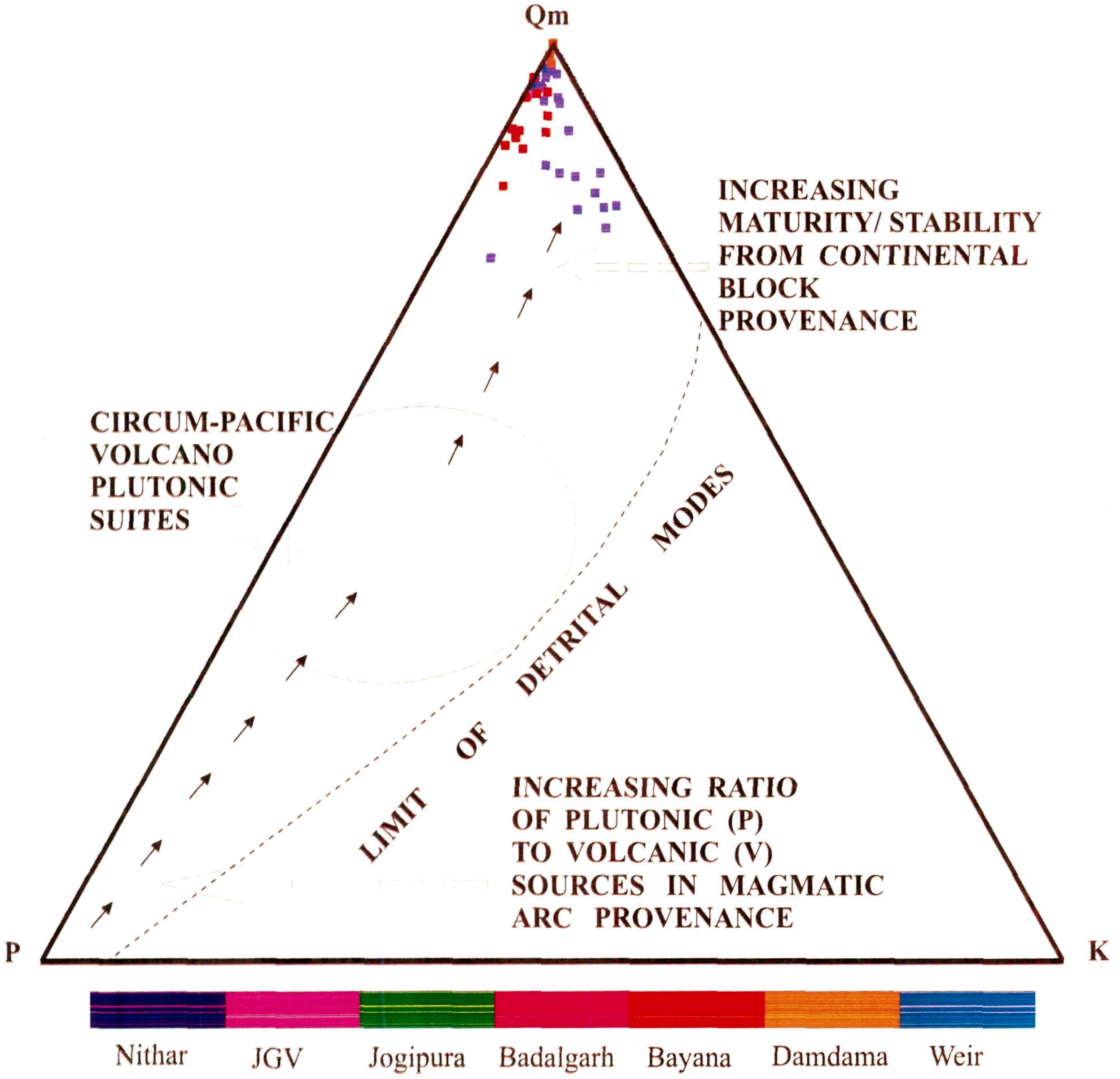

Figure 43. Qm-P-K plot of the sandstones of Bayana Basin, according to Dickinson (1985)

	1			2						7		
K9	99.88	0.11	-	94.0	0.11	5.88	100	-	-	99.88	0.11	-
WEIR FORMATION												
W1	91.26	-	8.73	89.08	-	10.91	100	-	-	100	-	-
W2	97.72	-	2.27	91.97	-	8.02	83.45	-	16.54	100	-	-
W3	98.41	-	1.58	91.27	-	8.72	100	-	-	100	-	-
W4	95.28	-	4.71	90.57	-	9.42	100	-	-	100	-	-
W5	100	-	-	96.25	-	3.75	100	-	-	100	-	-
W6	100	-	-	100	-	-	-	-	-	100	-	-
W7	100	-	-	96.19	-	3.80	100	-	-	100	-	-

TECTONO – PROVENANCE

Continental blocks are tectonically consolidated regions composed essentially of amalgamations of ancient orogenic belts that have been eroded to their deep seated roots and lack any relict genetic relief (Dickinson, 1985). The main source for craton-derived quartzose sands are low lying granitic and gneissic exposures of the shield areas, supplemented by recycling of associated flat-lying platform sediments (Dickinson and Suczek, 1979). The sands may be deposited in intracratonic basin or transported to marginal basins. Magmatic arcs are belts of positive relief composed dominantly of penecontemporaneous association of orogenic volcanic and plutonic igneous rocks, together with associated metamorphic wallrocks, produced by continuing subduction along arc-trench system. Recycled orogens include the deformed and uplifted supracrustals strata, dominantly sedimentary but also volcanic in part, exposed in varied fold thrust belts of orogenic regions.

The plots of Bayana Basin sandstones on Qt – F – L and Qm – F – Lt diagrams suggest that the detritus of the sandstones were derived from the granite-gneisses exhumed in the craton interior and medium to high-grade metamorphosed supracrustals forming recycled orogen provenance. This suggests derivation of the sandstones from stable parts of the craton, with perhaps an equal contribution from recycled orogens, shedding quartzose debris of continental affinity into the basin (Dickinson et al., 1983). Nevertheless, such provenance determination has to be considered with caution, because of the changes in the original composition which may be caused by diagenesis, leading to modification in the Qt-F-L plot (McBride, 1985).

In Qp-Lv-Ls plot, the sample data mostly fall in the mixed orogenic sand provenence with contribution from arc orogen source and fold thrust belt source. The Qm – P – K diagram suggests the maturity and stability of the source region. This may have stemmed from very long period of tectonic quiescence and mature geomorphology of the area. The composition and maturity of sands is primarily controlled by the source rock and tectonics, but, secondary processes, such as climate and weathering and depositional reworking and abrasion, acting singly or in combination, tends to destroy the labile constituents and produce quartz-rich sand. Intense weathering under warm and humid climate and long residence time in soils may destroy feldspar and other labile constituents, resulting in high degree of compositional maturity of sediments.

The relative abundance of monocrystalline quartz to that of polycrystalline quartz appears to reflect the maturity of the sediments, because polycrystalline quartz is eliminated by recycling and disintegrates in the zone of weathering as does strained quartz (Basu, 1985). The sandstones have considerably high percentage of monocrystalline quartz (84.68%) as compared to polycrystalline quartz (15.32 %), which indicates removal of polycrystalline quartz by weathering and recycling. Abundance of feldspar also serves as a guide to determine the maturity index since much of the feldspar is destroyed by weathering where relief is low and rainfall high. Generally small percentage of feldspar in the sandstone suggests that they were lost in the soil profile or by abrasion during transit or lost by solution during diagenesis. However, occurrence of weathered and fresh feldspars together indicates derivation from two different sources.

As discussed earlier, the formation of quartz-rich single-cycle sand requires low relief in the provenance to prolong the duration of weathering. It can, therefore, be inferred that Bayana Basin sandstones were derived from continental block provenance of low relief.

Considering regional perspective, Mesoproterozoic Delhi Supergroup deposits are wide spread in outcrop and the subsurface throughout the Aravalli-Delhi mountain belt. The Delhi Fold Belt consists of highly folded and deformed rocks exhibiting polyphase metamorphism, comprising deep-water to platformal sediments. Generally, the mountain belts represent regions where oceans might have opened and closed, and they are the products of continental collision (Dewey and Bird, 1970). These mountains had been eroded and had low relief, typical of tectonically stable cratonic areas. Plate tectonic processes of continental collision, suturing and consumption of the crust at plate margins, by thrusting or under-plating lead to crustal thickening and formation of orogenic belts in Phanerozoic and Proterozoic times. Knowledge of crustal structure and tectonics of the ancient collision belts can lead to better understanding of the mechanism of crustal growth processes, provided, later tectonic activity has not disturbed the original structure. Rift opening of the Delhi basins is now considered as well-established. The cratonic sediments were deposited in a shelf sea during the initial stage of basin opening. Studies on Delhi Supergroup rocks, carried out by different workers have shown that they were deposited in either fluvial or various coastal environments. In its northeastern part, Delhi basin exhibits several depositories which are smaller in size and are separated from each other by uplands. A series of north to north-east trending synsedimentary faults have been recognized by Singh (1982, 1984), which bound the depositories or sometimes acts as intrabasinal faults. As discussed earlier, paleocurrent data in the study area show that sediment dispersal was multidirectional, mostly from 'Dausa uplift' as well as from northern part of Rajputana craton. Taking into consideration the general sedimentation pattern in various grabens around Dausa uplift in northeastern Rajasthan, it is observed that fluvial dispersal was mostly to the north in all the depositories with exception in Lalsot graben (Singh, 1985). On the other hand, alternations of fluvial and coastal deposits are observed in other parts of this basin. This may be inferred that fluvial deposits were formed in a low-lying stable continental area during regression while fluvial and shallow-marine deposits are formed in the shelf margin during transgression (Wanas and Abdel-Maguid, 2006). In view of this, it can be considered that sediments in and around Dausa uplift were deposited on a low-lying landmass forming a stable continental shelf. This justifies the interpretation of tectono-provenance in the study area also.

The characteristic of the source terrains along the suture zones is large compositional range of the rocks (e.g., suture zones of Himalaya, Apennines and Pyrenees), which supply sediments to the adjacent basin. The large scale compositional variation of the Bayana sandstones also reflects the existence of a similar source terrain for these sandstones. However, in the entire suture zone, sandstones in general are more feldspathic than those of the modern and ancient foreland basins (Dickinson, 1985; DeCelles and Hertel, 1989). Most of the foreland basin sandstones plot in the recycled orogen field having fairly uniform composition (Dickinson, 1985) reflecting the dominance of sedimentary source rocks that are lifted and eroded from the thrust sheet and deposited in the foreland basin. Therefore, the second possibility appears more appropriate for the Bayana Basin sandstones.

Therefore, from the foregoing discussion and considering the analysis of data plotted on different triangular diagram, specially, spread of data in recycled orogen, fold thrust belt and rifted basin, a tectonic collage can be suggested as tectonic setting. This interpretation is also supported by the evolutionary history of Aravalli-Delhi fold belt (Sudgen et al., 1990 ; Deb et al. , 2001) and that of Bayana Basin itself. (Singh, 1985).

Diagenesis

CHAPTER - VII

DIAGENESIS

Diagenesis includes “all physicochemical, biochemical and physical processes modifying sediments between deposition and lithification at low temperatures and pressures characteristic of surface and near-surface environments” (Chilinger et al., 1967). The principal diagenetic processes include compaction, cementation, authigenesis, recrystallization, replacement and metasomatism. Diagenesis in clastic rocks is governed by many factors such as mineralogy, temperature, pressure, water composition, flow rates, dissolution and precipitation kinetics, availability of nucleation sites, porosity and permeability. Freshly deposited sand is a porous, non-equilibrium mixture of detrital minerals. This is achieved by reduction of porosity through compaction and precipitation of stable authigenic cements or grains.

In sandstones, diagenesis is controlled by many factors and processes such as texture, detrital composition, environment of deposition and associated lithology. Locally, they control the migration of fluids and chemical potential of the system. On a regional scale, tectonic setting of the basin, geothermal gradient, rate and extent of deposition and basin subsidence play a significant role. For sandstone, the processes can be classified into two broad categories – physical and chemical diagenesis. Both these processes operate simultaneously in response to the surrounding stress field in order to restore chemical equilibrium.

The physical diagenesis of the freshly deposited sand results in compaction of the sediments and pore volume reduction due to pressure. At the sediment water interface and at shallow level of burial, physical compaction takes place by the process of grain rearrangement by rotation, slippage, ductile deformation and grain fracturing without dissolution at grain contacts (Houseknecht, 1987). Continued physical compaction results in the increase in number of contacts per grain, which passes into a regime of chemical compaction characterized by intergranular pressure solution, after considerable depth of burial. The increased geothermal gradient and pressure results in dissolution of grain contacts and change their nature from point to long and interpenetrative contacts.

The chemical diagenesis includes reaction leading to chemical dissolution, corrosion and cementation. These reactions may start just after the deposition of sand and are controlled by oxidation and reduction at sediment water/atmosphere interface. Chemical potential of sediments and pore water chemistry plays an important role in the removal of various unstable phases and precipitation of new stable phases in diagenetic regime. The process of cementation results in loss of porosity as it occludes the pore spaces but is reversible in contrast to loss by compaction, which is irreversible. The cementing material may be carbonate, silica, iron oxide or clay minerals. The cementation process leads towards the precipitation of new minerals on the grains and into the voids from the pore fluids (saturated with silica, iron oxide or clay minerals). The minerals get precipitated under suitable physico-chemical conditions.

The present study on diagenesis of the Bayana Basin sandstones mainly focuses on compaction, porosity reduction and cementation. Compaction is the process of volume reduction expressed either as a percentage of the original voids present or of the original bulk volume. Although compaction affects mainly loose, unlithified sediments, the process may also have profound influences on well-cemented deposits as indicated by stylolitic contacts. The intergranular pore spaces of clastic sediments are eliminated by closer packing, crushing, deformation, expulsion of fluids and possibly, dissolving of grains. The rate of compaction and the decrease in porosity and permeability, as well as the rate of expulsion of fluids are believed to change with time, both vertically and horizontally in sedimentary basins.

The chemical precipitation of cements in the framework of sedimentary deposits is dependent on a supply of chemical elements by intrastratal solutions, usually moving solutions. An understanding of the process of compaction and lithification is required in the study of diagenesis in general in order to determine the direct influences of compaction and cementation as well as the time relationship between compaction and lithification.

METHODOLOGY

The study is based on 106 samples and the sandstone samples were cut into standard petrographic thin-sections. They were stained with cobaltinitrate for potassium feldspar recognition. 200 to 250 grains were counted per thin section. The traditional methods (Ingersoll et al., 1984) were used for classification and tabulation of grain types. Standard petrological techniques using a polarizing microscope were employed to describe the thin sections. Authigenic components (cement and matrix replacement constituents) were counted separately. Taylor's (1950) method was applied for the study of the nature of detrital grain contacts and for computation of contact index, that of Pettijohn et al. (1987) was used.

COMPACTION

The reduction in the bulk volume of rock is called compaction. It occurs in response to four types of processes: grain rearrangement, plastic deformation, dissolution and brittle deformation (Wilson and Staton, 1994). The process of compaction results in the expulsion of pore fluids and reduction in pore volume due to the load of overburden (Chlingarian, 1983). Compaction may modify the original framework composition of sandstone, which may be liable to misinterpretation. Many variables influenced compaction such as framework composition, amount and timing of cementation, texture, geothermal gradient and depth of burial.

Grain contacts

To understand aggregate packing, two parameters have been employed, i.e., contact type (Taylor, 1950) and contact index (Pettijohn et al., 1987). The contact type is counted along linear traverse grid points in a line and the contact index (CI) is counted at grid point spacing around the grain. The contact index CI is the average number of grain contacts a grain has in its surroundings, encountered at point spacing.

Taylor (1950) identified four types of grain-to-grain contacts in the plane of thin sections. Tangential or point (P) contacts, long contact (L) as a line, concavo-convex (C) contact as curve line and sutured (S) contact as serrated interfingering contact. In loosely packed sandstone some grains may not make any contact with other grains, such grains are referred as floating grains (F). Compaction changes the nature of grain contact and increased number of long and interpretative contacts (C, S) appear at the expense of floating grains and point contacts (F,P).

The framework constituents of the Bayana Basin sandstones exhibit mainly point contacts (67%) followed by long contacts (Figure 44), except in JGV Formation where floating grains are dominant (72%) followed by point contacts (28%) (Photo 17). As a whole average percentage of different types of contacts is as follows: point contact (67.97 %), long contact (21.91 %), floating grains (19.74 %), concavo-convex contact (2.18 %) and sutured contact (2.3 %). Taylor considered floating and point contacts to represent original packing. The long contacts result from little pressure and precipitated cement. High degree of compaction results in pressure solution giving rise to concavo-convex contacts (Photo 18). This is indicative of less compaction and pressure solution due to shallow burial or early cementation.

Except in JGV Formation, most of the grains are in contact with 4 grains, followed by > 4 grains and <4 grains. In JGV Formation majority of the grains are floating followed by grains having contact with 1 grain. The average contact index value of Bayana Basin sandstones is as high as 3.91 (Table 63). This is due to the dominance of point and long contacts in the framework constituents. Dominance of point and long contact is attributed to mechanical compaction which increases the value of contact index and packing density. Presence of significant numbers of suture (Photo 19) as well as concavo-convex contacts indicates that chemical compaction also played a role which resulted in pressure dissolution in point and long contact that converted them to concavo-convex and sutured contacts.

POROSITY REDUCTION

The original porosity of sediments is modified, i.e., either reduced or increased during diagenesis. In clastic sediments two main processes, which cause

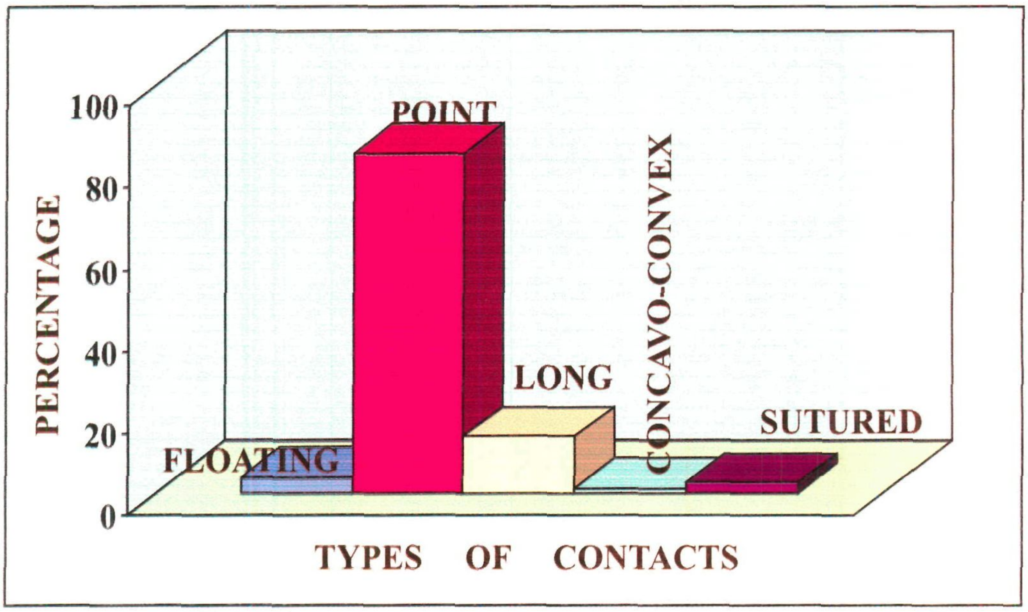

Figure 44. Distribution of various types of grain contacts in Bayana Basin Sandstones

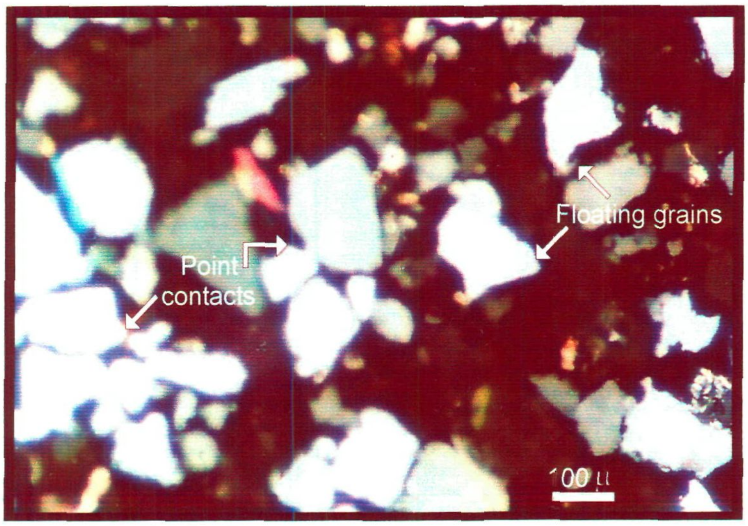

Photo 17. Microphotograph showing floating & point contacts in tuffacious sandstones of Jahaj-Govindpura Volcanic Formation.

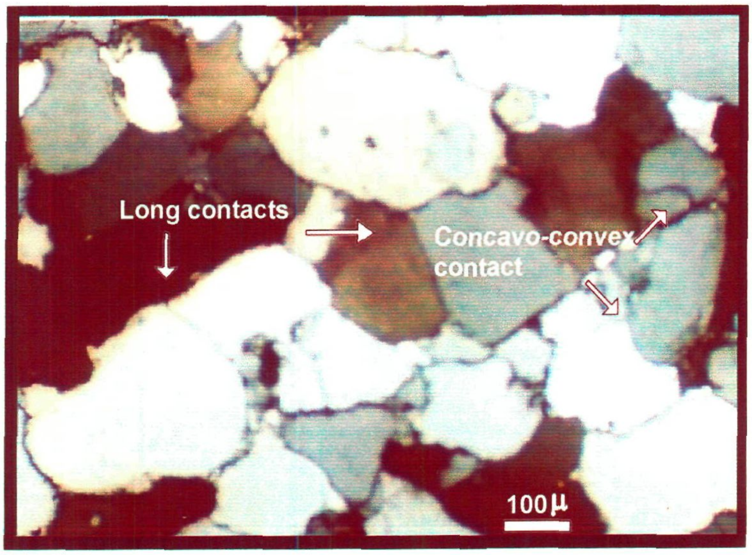

Photo 18. Microphotograph showing long & concavo-convex contacts in Jogipura Sandstones.

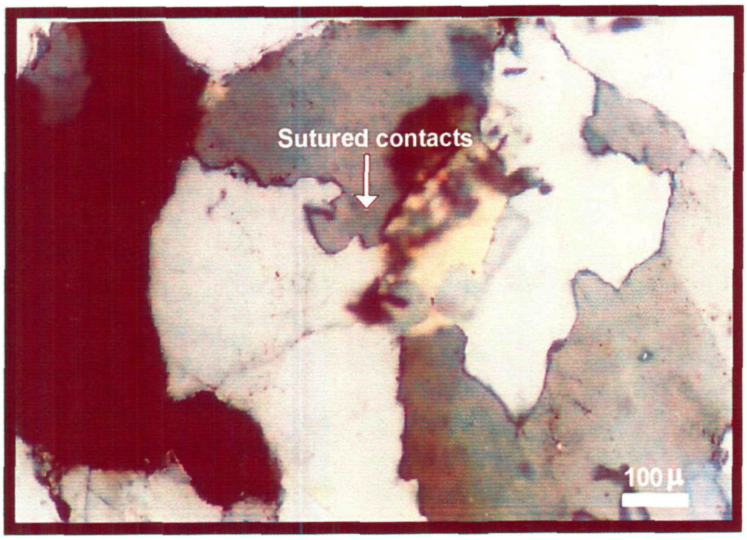

Photo 19. Microphotograph Showing Sutured contacts in Bhagrain locality of Badalgarh Formation.

reduction in porosity, are cementation and compaction. Porosity of the sandstones is studied in terms of existing optical porosity (EOP) and minus cement porosity (MCP). Heald (1956) defined 'minus-cement' porosity as the porosity, which would be present if a specimen contained no chemical cement, i.e., the porosity that existed before cementation took place. If minus-cement porosity of sandstone is almost equal to the original porosity of a freshly deposited sand, it would mean that the sandstone has suffered very little compaction before cementation. There have been several studies on random packing arrangements in sediments and in aggregates of spheres, which provide us with some information on initial porosities. Beard and Weyl (1973) showed that well sorted and artificially packed sands have porosities of about 39 percent, while Pryor (1973) studied recent sand bodies and obtained an initial porosity of about 45 percent. The depositional porosity for deltaic sands ranges between 42 to 50 percent (Atkins and McBride, 1992). The empirical porosity value is taken equal to 45 percent and with this value it is tried to model the porosity evolution and relative role of compaction and cementation.

Considering the above described relationship, minus-cement porosities of the studied sandstones were computed by adding the volume of cement to the volume of voids present. The volumes of cement and voids were measured in each thin section.

The existing original porosity (EOP) of the studied sandstones ranges from 2 to 12 and average is 3.59 (Table 64). These porosity values also include secondary porosity present in the form of cement dissolution pores and micropores in altered feldspars. Sandstones show minus cement porosity (MCP) values ranging between 6 to 26 Percent, averaging 18 percent. The study show that primary porosity of the rock is reduced by compaction and cementation through mechanical processes in the early stage of diagenesis and through chemical processes in the later stage, which finally results in generation of secondary porosity.

Table 63. Percentages of various types of grain contacts of the Bayana Basin sandstones.

Sample No.	Nature of grain contacts around grain point					Number of contacts per grain						Contact index
	Floating	Point	Long	Concavo-convex	Sutured	0	1	2	3	4	>4	
NITHAR FORMATION												
N4	-	77	20	0.9	2	-	36	17	60	15	7	2.7
N6	-	73	27	-	-	-	-	1	78	18	10	5.2
N9	-	82.7	17.3	-	-	-	-	-	81	20	21	5.6
N12	-	68.7	31.3	-	-	-	-	-	40	82	6	5.8
N14	-	90	10	-	-	-	-	-	69	31	10	5.4
N17	-	65	35	-	-	-	-	-	40	55	18	5.7
N19	-	69.9	30.1	-	-	-	-	-	47	25	10	4.09
N21	-	63	37	-	-	-	-	-	82	40	8	5.8
N22	-	60	39.9	-	-	-	-	-	51	58	19	5.9
N23	-	76.5	20.9	0.7	1.9	-	-	-	3	80	22	5.8
JAHAJ-GOVINDPURA VOLCANIC FORMATION												
V1	80	20	-	-	-	97	23	-	-	-	-	0.69
V3	78	22	-	-	-	80	22	-	-	-	-	0.71
V5	82	18	-	-	-	82	18	-	-	-	-	0.68
V7	71	29	-	-	-	75	30	-	-	-	-	0.78
V9	74	26	-	-	-	81	29	-	-	-	-	0.76
V11	62	38	-	-	-	59	36	-	-	-	-	0.87
V12	70	30	-	-	-	81	34	-	-	-	-	0.79
V14	74	26	-	-	-	72	25	-	-	-	-	0.75
V15	75	25	-	-	-	75	25	-	-	-	-	0.75
V17	77	22	-	-	-	81	23	-	-	-	-	0.72
V19	70	30	-	-	-	77	33	-	-	-	-	0.8
V21	66	34	-	-	-	63	32	-	-	-	-	0.83
V23	81	19	-	-	-	83	19	-	-	-	-	0.68
V25	71	29	-	-	-	75	30	-	-	-	-	0.78
V27	72	28	-	-	-	86	34	-	-	-	-	0.78
V29	96	4	-	-	-	96	4	-	-	-	-	0.54

V31	70	30	-	-	-	80	35	-	-	-	-	0.80
V32	65	35	-	-	-	69	36	-	-	-	-	0.84
V33	72	28	-	-	-	77	30	-	-	-	-	0.78
SITAKUND (JOGIPURA FORMATION)												
S2	9	82	9	-	-	10	-	10	-	50	40	4.31
S3	-	92	8	-	-	-	-	-	-	100	-	4.5
S4	-	84	16	-	-	-	-	-	20	100	-	4.3
S5	40	50	10	-	-	40	-	-	10	50	-	2.8
S8	-	85	10	5	-	-	-	10	7	100	-	4.26
S10	-	56	44	-	-	-	-	-	55	70	-	4.06
S12	15	60	25	-	--	15	-	-	25	60	-	3.6
S14	-	105	-	-	-	-	-	-	-	105	-	4.5
S16	4	84	12	-	-	5	--		-	-	102	4.9
S18	-	69	31	-	-	-	--	15	40	72	-	3.91
S20	10	62	28	-	-	10	-	18	39	-	29	3.5
S22	5	54	41	-	-	5	-	25	41	45	20	4.1
BHAGRAIN (BADALGARH FORMATION)												
Bg1	-	81.8	10	1.8	6.3	-	-	32	9	59	10	3.92
Bg2	-	68	28.8	1.6	1.6	-	3	4	82	30	6	3.7
Bg3	-	58.6	41.4	-	-	-	-	4	10	71	36	4.35
Bg5	-	78	20	2	-	-	8	15	37	12	28	3.59
Bg7	-	78	20	1	1	-	16	28	40	10	6	2.97
Bg9	-	73.9	26	-	-	-	12	8	36	29	30	3.99
ALAPURI (BADALGARH FORMATION)												
A1	-	67.9	32.1	-	-	-	-	8	32	72	28	4.3
A2	-	75.8	24.2	-	-	-	-	14	27	36	55	4.5
A4	-	69.9	30	-	-	-	-	-	38	59	66	4.6
A6	-	72.8	27.2	-	-	-	-	-	36	52	59	4.6
A8	-	62.3	37.7	-	-	-	-	-	33	39	50	4.6
A9	-	71.7	28.3	-	-	-	-	-	20	73	62	4.7
A11	-	62.1	37.9	-	-	-	-	-	23	53	48	4.7
BAYANA FORMATION												

B5	-	45	53	1	1	-	-	4	28	40	70	4.73
B8	2	85	13	-	-	-	-	-	7	60	43	4.82
B13	1	81	17	-	1	1	-	15	30	28	65	4.50
B18	6	67	20	-	7	24	10	50	-	6	-	1.98
B21	-	71	28	-	1	-	-	-	27	14	60	4.82
B25	-	90	10	-	-	-	-	7	-	15	78	5.14
B27	-	56	43	-	1	-	-	8	-	98	38	4.65
B30	5	74	20	-	1	5	4	-	15	93	25	4.01
B32	-	77	23	-	-	-	-	3	12	63	29	4.60
B35	1	84	15	-	-	1	-	-	90	8	4	3.62
B37	-	75	24	-	1	-	-	7	30	69	26	4.35
B40	3	70	24	1	2	3	-	-	60	34	42	4.28
B42	3	65	30	1	1	3	--	12	1	74	53	4.71
B45	2	83	12	1	2	2	-	-	-	79	22	4.63
B49	8	80	11	-	1	8	-	-	2	48	62	4.73
BHIMNAGAR (BAYANA FORMATION)												
BN1	12	68	19	-	1	19	13	22	20	28	15	3.09
BN3	14	17	67	-	2	17	2	1	5	20	80	4.49
BN5	6	58	35	-	1	5	3	10	28	17	60	3.64
BN8	8	23	64	-	5	10	3	2	5	65	55	4.47
BN10	14	49	36	-	1	12	2	2	5	15	96	4.75
BN12	5	29	63	0.9	2.1	-	-	4	5	30	98	5.12
BN14	7	76	15	1	1	10	15	30	97	10	5	3.08
BN16	5	63	32	-	-	5	3	2	12	30	90	4.81
BN18	5	70	23	1	1	5	5	2	9	80	35	4.40
BN19	9	63	26	2	-	9	3	3	15	96	20	4.18
BN20	2	78	20	-	-	2	4	10	102	30	35	3.91
BN22	-	66	29	3	2	-	-	-	15	74	25	4.58
BN24	5	67	27	-	1	5	-	-	2	67	28	4.55
BN27	8	69	21	-	2	8	-	4	-	70	22	4.32
BN29	4	26	68	1	1	4	-	-	4	68	26	4.55
BN31	10	76	14	-	-	10	-	3	5	86	10	4.14
BN33	-	84	16	-	-	-	-	-	-	96	20	4.67
UMRAIND (DAMDAMA FORMATION)												

U1	4.8	85.4	9.8	-	-	5	-	25	63	10	-	3.2
U3	-	77.9	22.1	-	-	-	-	-	40	43	26	4.3
U5	-	78.9	21.1	-	-	-	-	-	90	24	-	3.7
U6	1.8	88.7	9.5	-	-	3	-	-	92	12	-	3.5
U8	-	86.4	13.6	-	-	-	-	-	69	34	-	3.8
U9	-	87.5	12.5	-	-	-	-	-	61	46	13	4.1
U10	-	87.1	12.9	-	-	-	-	-	24	63	30	4.5
KANAWAR (DAMDAMA FORMATION)												
K1	-	83.4	16.5	-	--	-	-	-	69	34	-	3.8
K2	-	90.1	9.9	-	-	-	-	18	27	43	21	4.1
K4	-	89.7	10.3	-	-	-	-	-	31	69	-	4.1
K6	-	85.2	14.8	-	-	-	-	-	78	25	20	4.0
K8	-	87.4	12.6	-	-	-	-	-	63	54	-	3.9
K9	-	92.3	7.7	-	-	-	-	-	30	48	34	4.5
WEIR FORMATION												
W1	3.80	81.90	12.3	-	1.9	4	-	-	-	55	50	4.99
W2	-	87.29	8.18	1.81	2.72	-	-	-	-	58	52	4.97
W3	-	80.87	13.3	0.83	5	-	-	-	-	53	67	5.05
W4	-	92	6	1	1	-	-	-	-	45	47	4.89
W5	-	81.42	17.6	-	0.98	-	-	-	-	40	52	4.91
W6	-	82.30	17.7	-	-	-	-	-	-	42	65	5.10
W7	-	77	20	1	2	-	-	-	-	27	73	5.23

CEMENTATION AND MATRIX

Cementation is the process whereby new minerals are precipitated as syntaxial overgrowth in detrital 'seeds' or as authigenic phases into the pore spaces from intra-formational fluids. The cements are normally considered to cause loss of porosity but dissolution and leaching of cements may give rise to secondary porosity in contrast to porosity loss due to compaction, which is irreversible. The timing of cementation events is of much importance, specially quartz cements which may stabilize the framework. Four types of cements are identified in the Bayana Basin sandstones; viz., silica, iron oxide, carbonate and barite cement (Table 64).

Silica cement

Silica cement average 4.1 percent in the Bayana Basin sandstones. The silica overgrowths are clearly recognizable in those grains, which passes a thin brown limonitic coating marking the original grain boundary. Most overgrowths only partially fill the intergranular spaces whereas well-developed, overgrowths from adjacent grains meet along sharp and planar crystal faces (Photo 20). In some grains embayment resulting from corrosion and filled with brownish clay material, cut across the overgrowths. The overgrowths are more common around coarse grains than medium to fine grains of monocrystalline quartz population. The relationship between grain roundness and overgrowth indicates the overgrowths are more common on subrounded and rounded grains followed by subangular and angular. In few thin sections locally cryptocrystalline quartz seams are found instead of homotaxial overgrowth. The pressure solution of detrital quartz and other silicates at grain contacts are important source of silica in deeply buried sandstones. The possible source for cryptocrystalline quartz cement is intercalations of tuff and volcanic rock fragments, which are characteristics of marine sedimentation in rift basin.

Iron-oxide cement

Iron oxide occurs throughout the study area. It forms a dark brown black coating on the detrital quartz and feldspar grains as well as isolated patches and pervasive pore fillings (Photo 21). This coating is variable in thickness ranging from 15 to 25 microns. Similar coatings also occur around altered and leached feldspar grains. In many instances, the clastic grains have lost their grain morphology and are present now in the form of protrusions, embayments and notches. Iron oxide in sediments may have formed just after the deposition at the sediment water interface but were regenerated during burial (Walker, 1974).

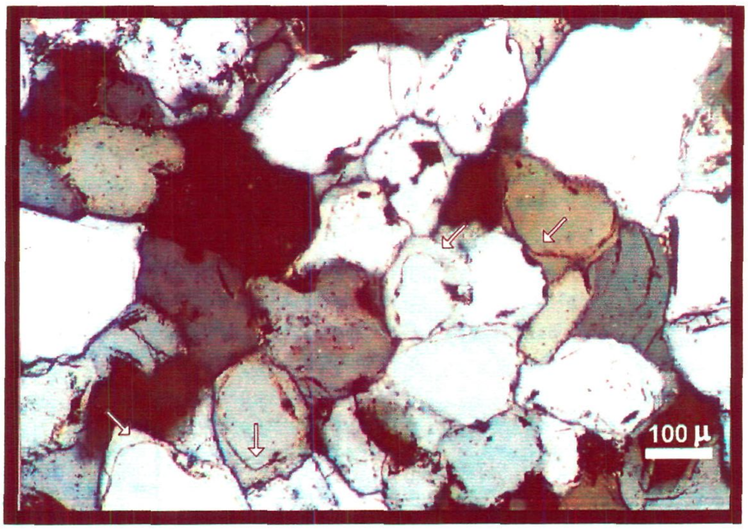

Photo 20. Microphotograph showing quartz overgrowth in Nithar Sandstones.

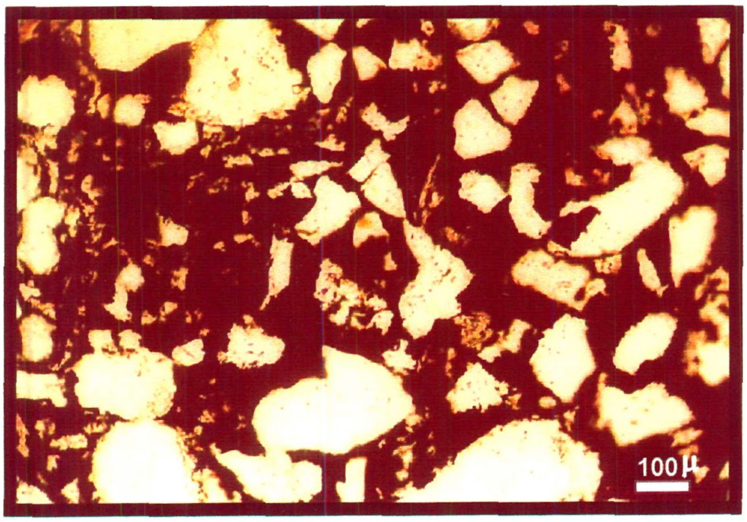

Photo 21. Microphotograph showing iron cement corroding quartz grain in Bhimnagar locality of Bayana Formation

Carbonate cement

Carbonate cement occurs in the form of sparry calcite and microcrystalline calcite cement. The boundaries of replaced detrital grains are markedly etched and corroded by adjoining calcite cement (Photo 22). The original framework of the sandstones has been modified as a result of replacement of detrital grains by calcite cement but this modification is not extensive in view of the patchy distribution of calcite cement and its limited occurrence. The replacement cementation clearly implies chemical instability of the quartz grains and a slow rate of cementation resulting in solution of the silicate grains (Dapples, 1979). The replacement of quartz by calcite implies that pore waters were undersaturated with respect to quartz and supersaturated with respect to calcite. The calcite cementation occurred slowly covering a large time span, which is evidenced by corroded quartz grains and indistinct boundary between quartz grains and carbonate cement. Quartz was corroded by the continued movement of fluids. Precipitation of microcrystalline calcite cement probably took place at shallow depth above water table by the process of concretion as evidenced by open framework entrapped iron oxide cement. It suggests that the depositional setting may have been intermittently exposed, allowing onset of pedogenic process that induced calcite cement precipitation. Later, during burial the micrites were replaced by sparry calcite in meteoric hydrologic regime along the interface zone of accretion and saturation (Ahmad et al. 2005).

Barite cement

Barite cement occurs in small amount mainly at Sitakund of Jogipura Formation. It occurs in patches specially in oversized pores and has corroded the detrital grains. Precipitation of barite in sediments was possibly received from the Archean barites associated with basic volcanics as recycled product during sedimentary cycles (Basu, 1998).

In the present study, in Nithar, JGV, Bayana and Weir Sandstones, silica and iron oxide are dominating cement (Table 64). The iron cement occurs as thin coating around detrital grains as well as isolated patches in between the grains. The silica cement occurs in the form of overgrowths on detrital grains and cryptocrystalline quartz seams. In Bayana sandstones, overgrowths are prominent and continuous, but in case of Nithar and JGV sandstones, these overgrowths are thin and discontinuous. Bayana sandstones show the sign of dissolution of feldspar. The Jogipura sandstones show iron, carbonate, silica and barite cements. Abundance of silica in the form of overgrowth is low indicating that compaction of the sandstones was limited which resulted very little pressure solution. Carbonate cement occurs as microcrystalline calcite and sparry calcite. The important aspects of calcite-cemented sandstones are corrosion of detrital grains. In Badalgarh Sandstones, diagenetic studies showed that silica is the dominating type of cement. The Damdama Sandstones show presence of silica and iron oxides as the dominating types of cement. The silica overgrowths fill the intergranular spaces and also on detrital grains. The quartz overgrowth is mainly developed on monocrystalline quartz when compared to polycrystalline quartz grains. Amongst monocrystalline the overgrowth is more common around undulose grains as compared to nonundulose grains. Most of the grains show moderately developed overgrowths followed by well-developed and poorly developed overgrowths. The iron cement occurs as thin iron coating around detrital grains, isolated patches and as void fillings.

MATRIX

In the studied sandstones, silty to clayey matrix is present in varying amounts. The matrix compositionally represents silt-size quartz and feldspar grains, volcanic lithics (Photo 23) mixed with fine-grained muscovite and clay are also present. Both syndepositional and post-depositional matrix is present. The matrix, therefore, influences diagenetic process by supplying chemical entities and bulk properties, such as porosity and permeability by pore occlusion. Very low amount of matrix present in few sandstones is probably decanted from infiltrating muddy pore water.

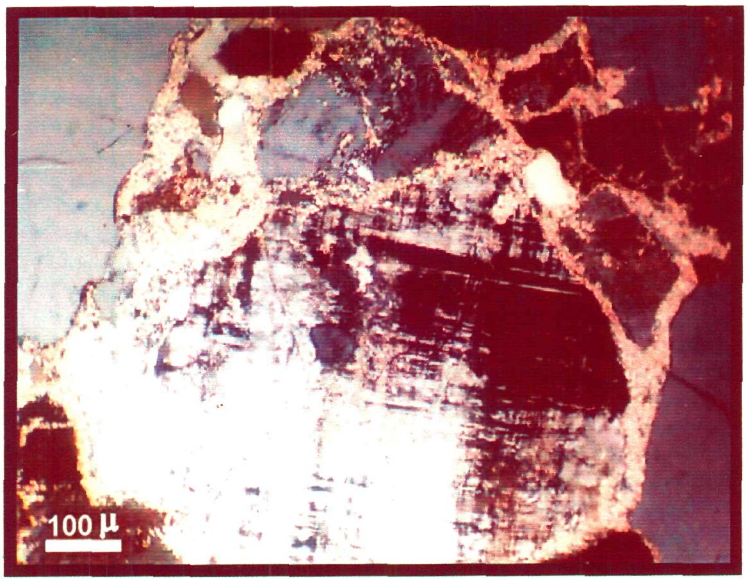

Photo 22. Microphotograph showing microcline corroded by carbonate cement in sandstones of Sitakund locality of Jogipura Formation.

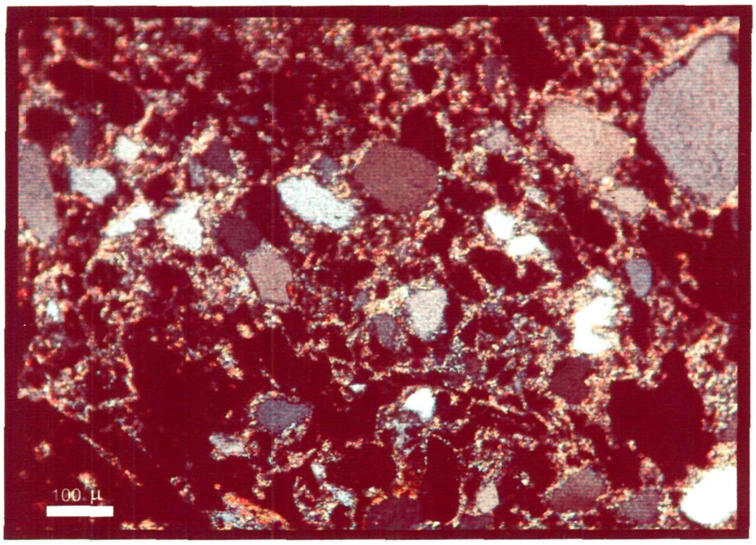

Photo 23. Microphotograph showing matrix corroded by quartz & volcanic lithic fragments in sandstones of Jahaj-Govindpura volcanic Formation

DIAGENETIC EVOLUTION

During early stage of diagenesis, mechanical compaction was the dominant process. It caused rotation and adjustment of grains and formation of point and long contacts. Generally original sandstone porosity is 45 %, which was reduced to an average of 18%. Three processes are commonly important in modifying intergranular porosity; mechanical compaction, chemical compaction and cementation. Houseknecht (1987) proposed a method to estimate quantitively the porosity loss by compaction using model analysis. Intergranular volume (Weller, 1958), which is synonymous with minus cement porosity, is the sum of intergranular porosity plus all cements that occupy the intergranular space. Intergranular volume is occluded and reduced by cementation and compaction during diagenesis. The studied sandstones are divided into two groups on the basis of diagenetic features i.e. one group that was subjected to more compaction than cementation and other group that was subjected to more cementation than compaction. Compaction, largely influenced by roundness of detrital particles was possible in the absence of an early major cementation phase that could have stabilized the detrital framework. Major diagenetic event was alteration of feldspars and dissolution. The feldspar grains show different stages of alteration. At places, complete dissolution of feldspar grains resulted in oversize pores. Dissolution and loss of feldspar can take place in the shallow weathering zone or in the deep surface (McBride, 1985). The shallow depth of burial and lack of illitization suggest that the feldspar in the studied sandstones were destroyed in the shallow, weathering zone.

Among the various cements, quartz was the first to be precipitated in the form of overgrowths partially filling in the interparticle pore space. The silica forming overgrowth was probably derived from dissolution of quartz grains and/or from compaction water. During downward passage of infiltrated waters through the zone of aeration produces pedogenic features including leached zones and horizons of accumulation of carbonate minerals. Precipitation of calcite took place in the meteoric hydrologic regime. Iron oxide formed due to weathering and pedogenic processes.

Table 64. Percentage of detrital grains, cement/matrix and types of porosity of Bayana Basin sandstones

Sample No.	Detrital grains	Cement / Matrix					Porosity	
		Iron	Carbonate	Silica	Matrix	Total cement/matrix	Existing optical porosity	Minus cement porosity
NITHAR FORMATION								
N4	82	3	-	3	9	15	3	18
N6	79	7	-	3	9	19	2	21
N9	87	3	-	1	2	6	7	13
N12	85	4	-	2	3	9	6	15
N14	78	7	-	4	6	17	5	22
N17	85	6	-	-	1	7	8	15
N19	81	6	-	1	3	10	9	19
N21	80	3	-	2	4	9	11	20
N22	78	6	-	3	5	14	8	22
N23	78	10	-	3	5	18	4	22
JAHAJ-GOVINDPURA VOLCANIC FORMATION								
V1	78	5	-	1	12	18	4	22
V3	79	2	-	-	14	16	5	21
V5	77	-	-	3	12	15	8	23
V7	80	-	-	3	12	15	5	20
V9	83	3	-	1	11	15	2	17
V11	80	3	-	-	13	16	4	20
V12	76	-	-	3	14	17	7	24
V14	79	3	-	3	10	16	5	21
V15	81	2	-	1	10	13	6	19
V17	78	1	-	2	9	12	10	22
V19	80	3	-	-	11	14	6	20
V21	82	4	-	-	10	14	4	18
V23	77	-	-	3	11	14	9	23
V25	76	3		-	13	16	8	24
V27	79	3	-	-	10	13	8	21
V29	83	2	-	-	8	10	7	17
V31	78	3	-	-	14	17	5	22
V32	80	4		-	12	16	4	20
V33	81	3	-		10	13	6	19
SITAKUND (JOGIPURA FORMATION)								
S2	82	-	10	-	4	14	4	18
S3	80	-	12	4	2	18	2	20
S4	85	-	5	2	5	12	3	15
S5	81	-	8	2	6	16	3	19
S8	88	-	3	5	2	10	2	12
S10	80	-	12	3	2	17	3	20
S12	77	-	12	3	8	23	-	23
S14	80	-	9	3	6	18	2	20

S16	78	-	15	3	4	22	-	22
S18	87	-	7	2	3	12	1	13
S20	85	-	10	-	4	14	1	15
S22	80	-	10	4	4	18	2	20
BHAGRAIN (BADALGARH FORMATION)								
Bg1	90	1	-	-	8	9	1	10
Bg2	92	2	-	-	3	5	3	8
Bg3	88	2	-	-	9	11	1	12
Bg5	94	1	-	-	3	4	2	6
Bg7	91	3	-	-	4	7	2	9
Bg9	87	2	-	-	10	12	1	13
ALAPURI (BADALGARH FORMATION)								
A1	88	6	-	-	3	9	3	12
A2	83	6	-	-	7	13	4	17
A4	79	7	-	1	9	17	4	21
A6	81	4	-	-	8	12	7	19
A8	78	5	-	-	12	17	5	22
A9	82	3	-	-	8	11	7	18
A11	79	6	-	-	9	15	6	21
BAYANA FORMATION								
B5	85	2	-	9	2	13	2	15
B8	78	5	-	11	4	20	2	22
B13	81	2	-	8	3	13	6	19
B18	83	1	-	10	3	14	3	17
B21	75	3	-	9	8	20	5	25
B25	87	3	-	4	3	10	3	13
B27	76	6	-	11	4	21	3	24
B30	80	4	-	12	2	18	2	20
B32	89	2	-	4	2	8	3	11
B35	79	5	-	9	5	19	2	21
B37	77	2	-	12	6	20	3	23
B40	82	4	-	6	4	14	4	18
B42	80	5		7	6	16	4	20
B45	75	3	-	11	8	22	3	25
B49	76	6	-	9	4	19	5	24
BHIMNAGAR (BAYANA FORMATION)								
BN1	80	1	-	4	3	8	12	20
BN3	85	2	-	6	4	12	3	15
BN5	82	5	-	5	3	13	5	18
BN8	88	3	-	4	3	10	2	12
BN10	83	6	-	3	6	15	2	17
BN12	93	2	-	3	1	6	1	7
BN14	86	6	-	6	1	13	1	14
BN16	85	1	-	6	3	10	5	15
BN18	86	4	-	5	2	11	3	14
BN19	83	2	-	9	2	13	4	17

BN20	79	4	-	6	6	16	5	21
BN22	89	2	-	5	2	9	2	11
BN24	90	2	-	4	3	9	1	10
BN27	87	3	-	5	4	12	1	13
BN29	85	3	-	6	3	12	3	15
BN31	78	3	-	10	4	17	5	22
BN33	82	3	-	8	4	15	3	18
UMRAIND (DAMDAMA FORMATION)								
U1	78	3	-	5	14	22	-	22
U3	82	2	-	7	7	16	2	18
U5	80	5	-	3	12	20	-	20
U6	81	2	-	8	10	19	-	19
U8	83	3	-	4	9	16	1	17
U9	79	5	-	3	13	21	-	21
U10	80	1	-	4	14	19	1	20
KANAWAR (DAMDAMA FORMATION)								
K1	84	8	-	3	3	14	2	16
K2	81	2	-	8	9	19	-	19
K4	88	6	-	1	4	11	1	12
K6	82	2	-	8	6	15	3	18
K8	80	5	-	6	7	18	2	20
K9	87	4	-	3	6	13	-	13
WEIR FORMATION								
W1	1	3	-	3	4	9	1	10
W2	84	-	-	11	2	13	2	15
W3	85	-	-	13	2	15	-	15
W4	74	-	-	17	2	19	7	26
W5	88	2	-	7	1	10	2	12
W6	82	2	-	13	1	16	2	18
W7	83	4	-	8	2	14	3	17
Grand Avg.(%)	80.6	2.9	1.06	4.1	6.01	14.1	3.59	17.6

Summary & Conclusions

SUMMARY AND CONCLUSION

The Delhi basin extends over a strike length of more than 700 km in NE-SW direction and has a maximum width of 120 km in the northeast Rajasthan. In its northeastern part, the Delhi basin consists of several structural depositories, which receive 3-10 km thick volcanic and sedimentary successions belonging to Delhi Supergroup. The Bayana Basin defining eastern most limit of the great Delhi basin is a fossil graben with over 3000m thick metavolcanics and metasedimentary successions. The Bayana Basin is located 45 km south-west of Bharatpur. It is confined between latitudes $26^0 53'$ and $27^0 02'$ north and longitudes $77^0\ 00'$ and $77^0 18'$ east. The infillings Bayana Basin is composed of around 3000m thick metasedimentaries and metavolcanics sequence of conglomerates, sandstones, shales, basal volcanic flows and volcanoclastics having faulted contact with pre-Delhi rocks along its southeastern fringe. Stratigraphically, Bayana Basin successions can be classified into 3 groups separated by two unconformities. Each of this group has been further sub-divided into formations and members in conformity with the 'code of stratigraphic nomenclature of India'.

In the present work, an attempt has been made to interpret various lithofacies belonging to seven formations of the Bayana Basin with reference to depositional processes and sedimentary environments in different localities of the study area to summarize a depositional model as well as to document the sandstones petrography, diagenetic aspects etc. to suggest possible interpretation of the provenance and tectonic setting.

The study area of Bayana Basin of Delhi Supergroup rocks is constituted of a heterogeneous assemblage of conglomerate, sandstones and shale; occur as scattered outcrops in the area of study. In the present work, seven Lithostratigraphic sections representing seven formations of Delhi Supergroup are described. Generally the Bayana sandstones exhibit variable colors of pink, brownish yellow, yellow etc. Most of the sandstones are hard and compact, massive although friable occasionally. The lithofacies exhibit vertical variations in the primary sedimentary structures. These structures include planar and trough cross-bedding, herring-bone cross-bedding, ripple marks, channel sandstone body, laminations etc. Lithostratigraphic sections are measured and are analyzed in the field, representative sandstone samples are collected for petrographic examination. The study is based on 106 samples. The sandstone samples were cut into standard petrographic thin-sections. They were stained with cobaltinitrate for potassium feldspar recognition. 250 to 300 grains were counted per thin section. The traditional methods (Ingersoll et al. 1984) were used to classify and tabulation of grain types. Standard petrological techniques using a polarizing microscope were employed to describe the thin sections. Authigenic components (cement and matrix replacement constituents) were counted separately. The heavy mineral separation was done by following Carver (1971), and identification was undertaken following Krumbein and Pettijohn (1938) as well as Milner (1962). Taylor (1950) method was applied for the study of the nature of detrital grain contacts and for computation of contact index, the method of Pettijohn et al. (1987) was used. The diagenetic process of sandstones was taken into account to check the modification of original detrital composition while attempting interpretation of provenance. Detrital mineralogy of the sandstones, including light and heavy mineral fractions were studied for the purpose of petrographic classification of the sandstones and interpretation of their provenance. Classification schemes of Folk (1980) based on composition of detrital constituents and Dickinson (1985) scheme based on the tectonic setting of the provenance were used.

Fourteen lithofacies are defined based on lithology, sedimentary structures, geometry and palaeocurrent directions. The lithofacies are named and coded individually following Miall's (1977) scheme. The depositional processes and environment have been employed to categorize four main genetic lithofacies assemblages. Facies assemblage A is constituted of lithofacies like tabular/trough cross-bedded sandstones, herring-bone cross-bedded sandstones, interbedded sequence of clast-supported polymictic conglomerate and sandstone, matrix-supported conglomerate interbedded with medium to fine-grained, cross-bedded sandstones etc and represents tidally influenced fluvial deposits. Facies assemblage B consists of a tabular package of tabular cross-bedded sandstones, herring-bone cross-bedded sandstone, trough cross-bedded sandstones, ripple-bedded sandstones, parallel laminated sandstones along with interbedded shale-thinly bedded fine-grained sandstone facies and it represents Tidalflat/Intertidal deposits. Facies assemblage C represents Tidal channel deposits and is characterized by the presence of four lithofacies; large scale trough cross-bedded sandstones, large scale tabular cross-bedded sandstones, parallel-laminated sandstones and channel sandbodies. Finally, Facies assemblage D represents wave & storm dominated shoreface Deposits and is made up of symmetrical & asymmetrical ripple bedded sandstones, interference ripple-bedded sandstones, tabular and trough cross-bedded sandstones in large as well as small scale, swaley-type trough cross-bedded sandstones, hummocky cross-bedded sandstone, laminated sandstones and pebbly sandstones facies. These contrasting palaeoenvironmental settings suggest deposition at a basin margin, through several episodes of transgression and consecutive regression, evidence of which are well-documented in the study area. Bimodal to quadrimodal distribution pattern of palaeocurrent for different formations of Bayana Basin indicate dispersal of sediment by multidirectional currents in nearshore shallow marine environment (Klein 1967, Selley 1967). The composite distribution of cross-bedding azimuths aggregated from the study area indicates dispersal of sediments from four different directions, indicating multidirectional clastic transport in offshore, onshore and longshore direction (Singh 1991). The source rocks were most probably the Dausa uplift as well as Rajputana Craton (Singh 1985) as the Bayana sedimentary rocks rest on the Archean basement (BGC) and Proterozoic Supracrustals (Aravalli Supergroup) with a pronounced unconformity in between.

Petrographic studies reveal that average grain-size is 2.04 Φ, grains are moderately well sorted. Most of the grains are subangular to subrounded and have low sphericity. Bivarient plotting of various parameters shows the relationship between mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting as moderate (positive as well as inverse). Overall texture of the Bayana Basin sandstone can be considered as submatured. According to Folk (1980) classification, the sandstones are mainly quartzarenite. The framework grains are mainly quartz (>90 % of rock volume) and less frequently of feldspar, rock fragments and heavy minerals. Most of the quartz grains are monocrystalline, rest being polycrystalline. The monocrystalline quartz generally shows undulatory extinction. Polycrystalline quartz grains possess both sharp and sutured intercrystalline boundaries. Feldspars include Plagioclase, orthoclase and microcline, altered to some extent. Both biotites as well as large flakes of muscovite mica are observed. Rock fragments include chert, shale, schist, quartzites etc. Average detrital mineralogy includes monocrystalline quartz (84.68 %), polycrystalline recrystalized quartz (4.18 %), stretched metamorphic quartz (2.36 %), feldspar (3.98 %), mica (1.09 %), rock fragments (3.43 %) and heavy minerals (0.27%). Average compositions of heavy minerals in these samples are as follows: opaque (87.6 %), tourmaline (3.35 %), biotite (3.1 %), muscovite (2.5 %), garnet (1.0 %), epidote (0.5%), zircon (0.5%), rutile (0.5%), and staurolite (0.5%).The detrital grains of Bayana Basin are in the sand size range and derived from only 100 km distance from Dausa uplift and Rajputana craton (Singh,1985). Due to presence of small amount of feldspar and rock fragments in the studied sandstone, prolonged reworking and presence of high gradient stream is quite likely within the basin.

The studied sandstones are divided into two groups on the basis of diagenetic features like one group that was subjected to more compaction than cementation and other group that was subjected to more cementation than compaction. In Nithar, JGV Bayana, Damdama and Weir sandstones, silica and iron oxide are the dominating types of cement. The Jogipura Sandstones show dominance of carbonate, silica and barite cements. In Badalgarh Sandstones, diagenetic studies showed that silica is the dominating types of cement. The sandstones consist of silty and clayey matrix. The matrix compositionally represents fine-grained monocrystalline and polycrystalline quartz, mica as muscovite and sedimentary as well as metamorphic rock fragments like siltstones, quartzite, schists, volcanic lithics and feldspars. In Nithar and Jogipura sandstones matrix is clayey (post depositional). Bayana sandstones show silty (syndepositional) matrix. The framework constituents of the Bayana Basin sandstones exhibit mainly point contacts (67%) followed by long contacts, which explains the high value of average contact index in the studied samples. Porosity of the sandstones is studied in terms of existing optical porosity (EOP) and minus cement porosity (MCP). Average percentage of EOP is 3.92 and average MCP percentage is 17.83. The primary porosity of the rock is reduced by compaction and cementation through mechanical processes in the early stage of diagenesis, and through chemical processes in the later stage, which finally resulted in generation of secondary porosity. Generation of secondary porosity influenced the minus cement porosity to increase. Compaction, largely influenced by roundness of detrital particles was possible in the absence of an early major cementation phase that could have stabilized the detrital framework. Major diagenetic event was alteration of feldspars, dissolution. The feldspar grains show different stages of alteration. At places, complete dissolution of feldspar grains resulted in oversize pores. Dissolution and loss of feldspar can take place in the shallow weathering zone or in the deep surface (McBride, 1985). The shallow depth of burial and lack of illitization suggest that the feldspar in the studied sandstones were destroyed in the shallow weathering zone. Investigation of heavy mineral types revealed the occurrence of zircon, tourmaline, and rutile which suggest an origin from igneous (plutonic) source rocks. Again, presence of epidote, garnet and staurolite indicate a source in metamorphic rocks (Morton et al. 1992; Wanas et al. 2006). Thus the suite of heavy mineral in the Bayana sandstones indicates source rocks which differ from igneous to metamorphic.

To understand the tectonic settings of the Bayana Basin sandstones, all the petrofacies were plotted in the Qt-F-L, Qm-F-Lt, Qp-Lv-Ls, Qm-P-K standard diagram, given by Dickinson (1985). The characteristic of the source terrains along the suture zones is large compositional range of the rocks (e.g., suture zones of Himalaya, Apennines and Pyrenees), which supply sediments to the adjacent basin. The large scale compositional variation of the Bayana sandstones also reflects the existence of a similar source terrain for these sandstones. However, in the entire suture zone, sandstones in general are more feldspathic than those of the modern and ancient foreland basins (Dickinson, 1985; Decelles and Hertel, 1989). Most of the foreland basin sandstones plot in the recycled orogen field having fairly uniform composition (Dickinson, 1985) reflecting the dominance of sedimentary source rocks that are lefted and eroded from the thrust sheet and deposited in the foreland basin. Therefore, the second possibility appears more appropriate for the Bayana sandstones. The Qt-F-L diagram which emphasizes factors controlled by provenance, relief, weathering and transport mechanism is based on total quartzose, feldspars and lithic content. Most of the samples lie in continental block provenance field suggesting contribution from the craton interior with basement uplift. Rest of the samples fall in the recycled orogen provenance which suggest their derivation from metasedimentary and sedimentary rocks that were originally deposited along former passive continental margins (Dickinson, 985). The Qm-F-Lt plot showed that the samples fall in Continental block provenance with little contribution from the Recycled orogen Provenance. In the Qm-P-K diagram, the data lie in the Continental block provenance reflecting maturity of sediments and stability of source area. In Qp-Lv-Ls plot, the sample data mostly fall in the mixed orogenic sand provenence with contribution from arc orogen source and fold thrust belt source. Here analysis of data from the plotting of triangular diagram doesn't exactly suggest the same interpretation which is due to the weathering and post-diagenetic modification of the unstable minerals. Considering the analysis of data plotted on different triangular diagram, a tectonic collage can be suggested as tectonic setting. This interpretation is also supported by the evolutionary history of the Bayana Basin.

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